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EXHAUST EMISSIONS CHARACTERISTICS FOR A GENERAL AVIATION LIGHT---ETC(U)
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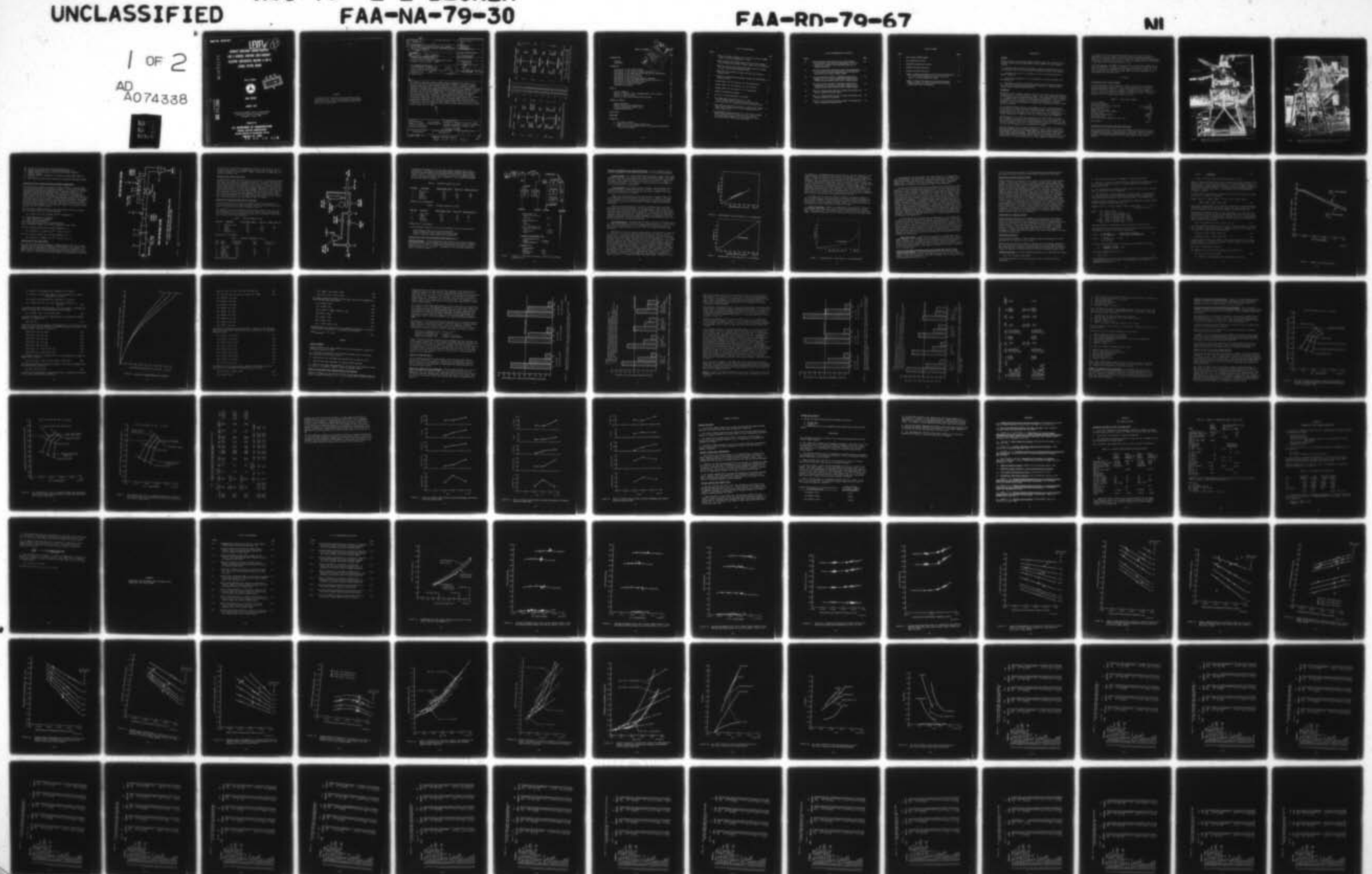

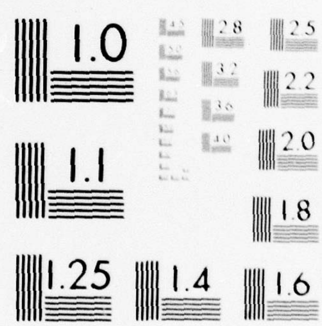

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Report No. FAA-RD-79-67

LEVEL II

EXHAUST EMISSIONS CHARACTERISTICS FOR A GENERAL AVIATION LIGHT-AIRCRAFT TELEDYNE CONTINENTAL MOTORS 6-285-B (TIARA) PISTON ENGINE

Eric E. Becker

FINAL REPORT

AUGUST 1979

Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
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16. Abstract

The Teledyne Continental Motors 6-285-B engine (S/N700106) was tested at the National Aviation Facilities Experimental Center (NAFEC) to develop an exhaust emissions data base. This data base consists of current production baseline emissions characteristics, lean-out emissions data, effects of leaning-out the fuel schedule on cylinder head temperatures, and data showing ambient effects on exhaust emissions and cylinder head temperatures. The engine operating with its current full-rich production fuel schedule could not meet the proposed Environmental Protection Agency (EPA) standard for carbon monoxide (CO) under sea level standard-day conditions. The engine did, however, meet the proposed EPA standards for unburned hydrocarbons (HC) and oxides of nitrogen (NO_x) under sea level standard-day conditions. The results of engine testing under different ambient conditions are also presented, and these results show a trend toward higher levels of emissions output for CO and HC under warm-or hot-day conditions while producing slightly lower levels of NO_x.

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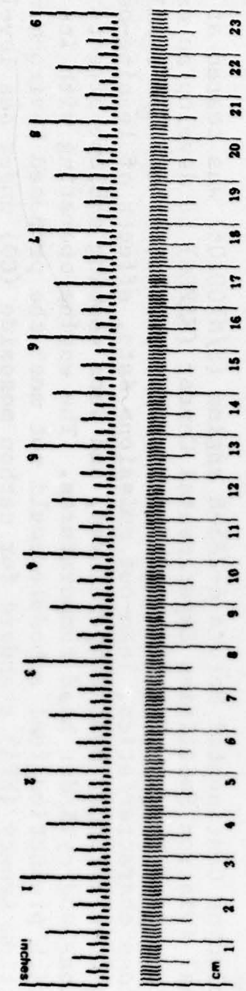
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

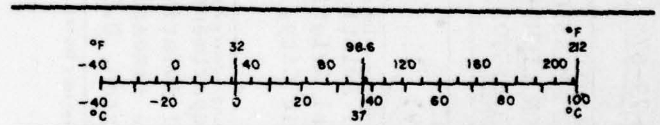


TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATION (Continued)

LIST OF TABLES

INTRODUCTION

PURPOSE.

General aviation piston engine exhaust emission tests were conducted at the National Aviation Facility Experimental Center (NAFEC) for the following reasons:

1. Determine and establish total exhaust emissions characteristics for a representative group of current production general aviation piston engines.

2. Determine the effects of leaning-out of the fuel metering system on exhaust emissions.

3. Verify the acceptability of test procedures, testing techniques, and instrumentation.

4. Determine reductions in operating limits and safety margins resulting from fuel system adjustments/modifications evaluated for improved piston engine exhaust emissions characteristics.

BACKGROUND.

Beginning in 1967, Congress enacted a series of laws which added environmental considerations to the civil aviation safety, control, and promotional functions of the Federal Aviation Administration (FAA). This legislation was in response to the growing public concern over environmental degradation. Thus, the FAA was committed to the development, evaluation, and execution of programs designed to identify and minimize the undesirable environmental effects attributable to aviation.

In accordance with the Clean Air Act Amendments of 1970, the Environmental Protection Agency (EPA) established emission standards and outlined test procedures when it used EPA rule part 87 in January 1973. The Secretary of Transportation and, therefore, the FAA was charged with the responsibility for issuing regulations to implement this rule and enforcing these standards.

Implementation of this rule was contingent on the FAA's finding that safety was not impaired by whatever means was employed to achieve the standards. For this reason the FAA undertook a program, subsequent to the issuance of the EPA emission standards in July 1973, to determine the feasibility of implementation, to verify test procedures, and to validate test results.

There was concern that the actions suggested in order to comply with the EPA emission standards, such as operating engines at leaner mixture settings during landing and takeoff cycles, might compromise safety and/or significantly reduce engine operating margins. Therefore, the FAA contracted with Avco Lycoming and Teledyne Continental Motors (TCM) to select engines that they considered typical of their production, test these engines as normally produced

to establish a baseline emissions data base, and then alter (by lean-out adjustments) the fuel schedule and ignition timing to demonstrate methods by which the proposed EPA limits could be reached and identify hazardous operating conditions. Independent verification of data was accomplished by the FAA at NAFEC by the duplication of the manufacturer's tests.

This report presents the NAFEC test results for the TCM 6-285-B (TIARA) piston engine (S/N700106). It should be noted that since the time of these tests, the EPA has rescinded the promulgated piston engine standards (reference 1). This work is reported upon herein in the same light as it would have been if the requirements were still in effect.

DISCUSSION

DESCRIPTION OF TCM 6-285-B (TIARA).

The 6-285-B engine tested at NAFEC is a geared fuel injected, horizontally opposed engine with a nominal 406 cubic inch displacement (cid), rated at 285 brake horsepower (bhp) for a nominal brake specific fuel consumption (bsfc) of 0.50. This engine is designed to operate on 100/130 octane aviation gasoline (appendix A--Fuel Sample Analysis of NAFEC Test Fuel). The vital statistics for this engine are provided in table 1.

TABLE 1. TCM 6-285-B (TIARA)

No. of Cylinders	6
Cylinder Arrangement	HO
Max. Engine Takeoff Power (HP, RPM)	285, 4000/2000*
Bore and Stroke (in.)	4.875x3.625
Displacement (cu. in.)	406
Weight, Dry (lbs)--Basic Engine	375
Propeller Drive	Geared
Fuel Grade--Octane Rating	100/130
Compression Ratio	9.0:1
Max. Cylinder Head Temperature Limit (°F)	460
*Drive Ratio	0.50:1

DESCRIPTION OF TEST SET-UP AND BASIC FACILITIES.

For the NAFEC sea level static tests, the engine was installed in the propeller test stand shown in figures 1 and 2. This test stand was located in the NAFEC General Aviation Piston Engine Test Facility. The test facility provided the following capabilities for testing light aircraft piston engines:

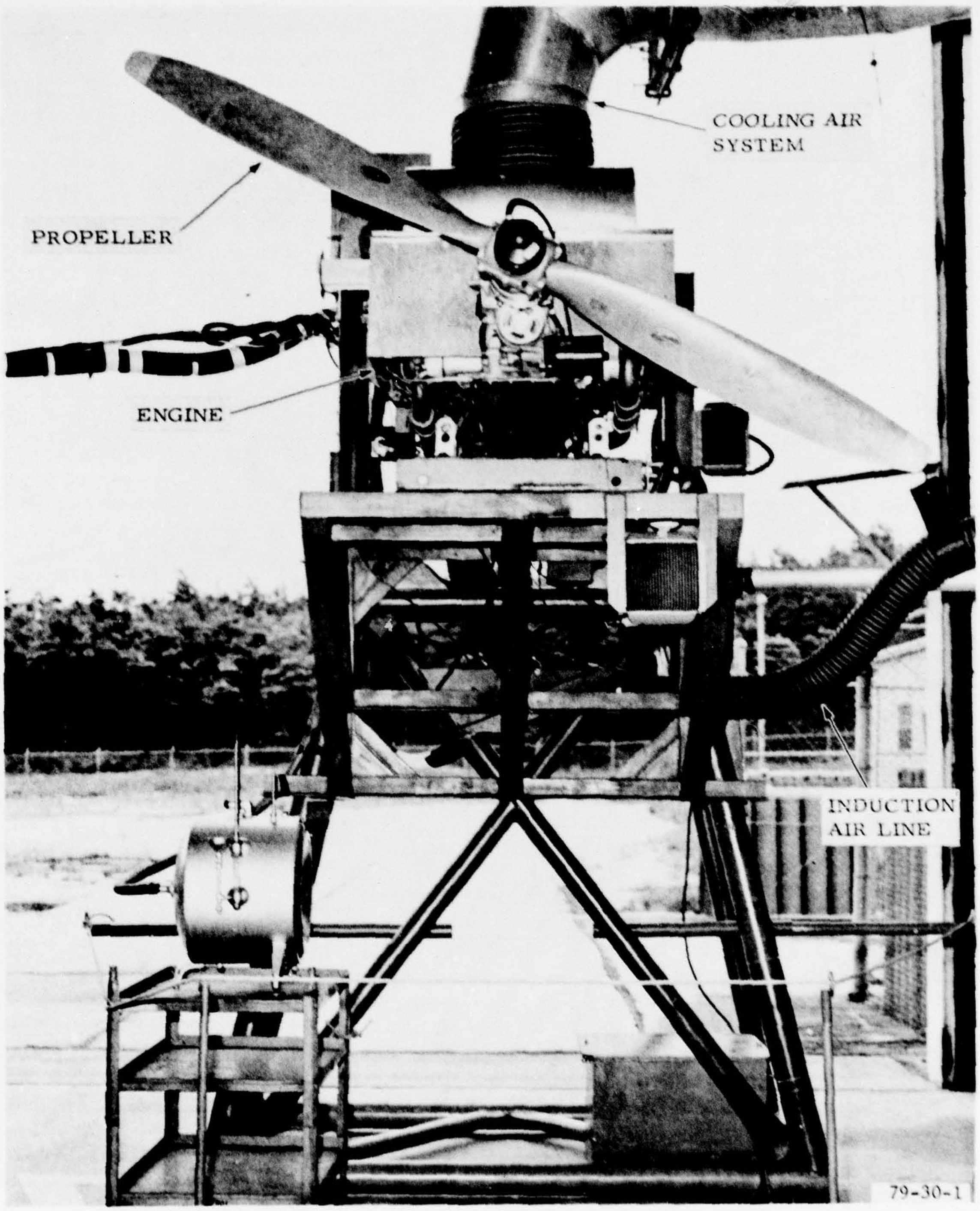


FIGURE 1. TYPICAL SEA LEVEL PROPELLOR TEST STAND--TCM 6-285-B (TIARA) ENGINE INSTALLATION-EMISSIONS TESTING

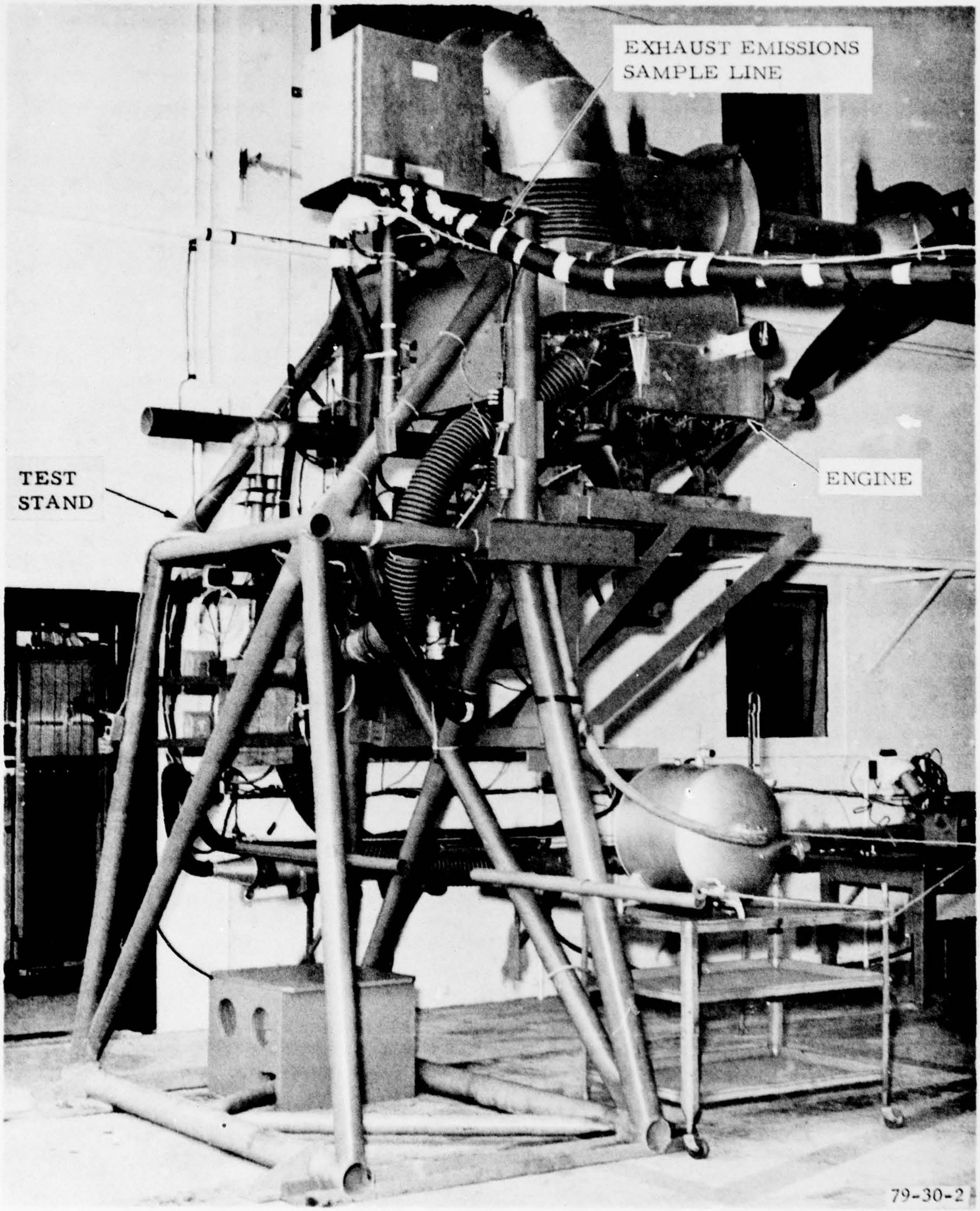


FIGURE 2. ENGINE INSTALLATION--NAFEC GENERAL AVIATION PISTON ENGINE TEST FACILITY--TCM 6-285-B (TIARA) ENGINE TEST INSTALLATION

(1) Two basic air sources--dry bottled and ambient air
(2) Ambient temperatures (20 to 140 degrees Fahrenheit (°F))
(3) Nominal sea level pressures (28.50 to 31.50 inches of mercury absolute (inhgA)
(4) Humidity (specific humidity--0 to 0.020 lb of water (H_2O) vapor/lb dry air)
(5) Fuel (100/130 octane aviation gasoline--a dedicated 5,000-gallon tank)

DESCRIPTION OF AIR INDUCTION SYSTEM AND AIRFLOW COMPUTATIONS.

The airflow system (induction system) utilized at NAFEC for testing light-aircraft piston engines is illustrated in figure 3. This system incorporated a redundant airflow measuring system for accuracy and reliability. In the high-flow measuring section NAFEC utilized a 3.792-inch orifice and an Autronics air meter (model 100-750S). The capability of this high-flow system ranged from 500 to 3,000 pounds per hour with an estimated tolerance in flow accuracy of ± 2 percent. The low-flow measuring section utilized a small 1.375-inch orifice and an Autronics air meter (model 100-100S). The capability of this system ranged from 50 to 500 pounds per hour with an estimated tolerance in flow accuracy of ± 3 percent. The size of the basic air duct was 8.0 inches (inside diameter) for the high-flow system and 2.0 inches (inside diameter) for the low-flow system.

The airflow was computed from the orifice differential pressure and induction air density using the following equation:

$$Wa = (1891)\ (C_f)\ (d_o)^2\ [(.03609)\ \Delta P_\rho]^{1/2} \quad \text{(Reference 2)}$$

ΔP = inH_2O (differential air pressure)
ρ = lb/ft^3 (induction air density)
d_o = inches (orifice diameter)
C_f = flow coefficient for orifice (nondimensional)
1891 = conversion constant for airflow in pounds per hour (lb/h).

For the 3.792-inch orifice this equation simplifies to:

$$Wa = (16{,}994.5)\ [\ (.03609)\ \Delta P_\rho]^{1/2} = 3228.5\ (\ \Delta P_\rho)^{1/2}$$

For the 1.375-inch orifice this equation simplifies to:

$$Wa = (2{,}484.7)\ [(.03609)\ \ \Delta P_\rho\ ]^{1/2} = 472.03\ (\ \Delta P_\rho\ )^{1/2}$$

DESCRIPTION OF FUEL FLOW SYSTEM.

The fuel flow system utilizied during the NAFEC light-aircraft piston engine emission tests incorporated rotameters, turboflow meters, and a burette. The high-flow section incorporated a rotameter in series with a high-flow turbometer, while the low-flow section incorporated a low-flow turbometer in series with a burette. The high-flow system was capable of measuring fuel flows from

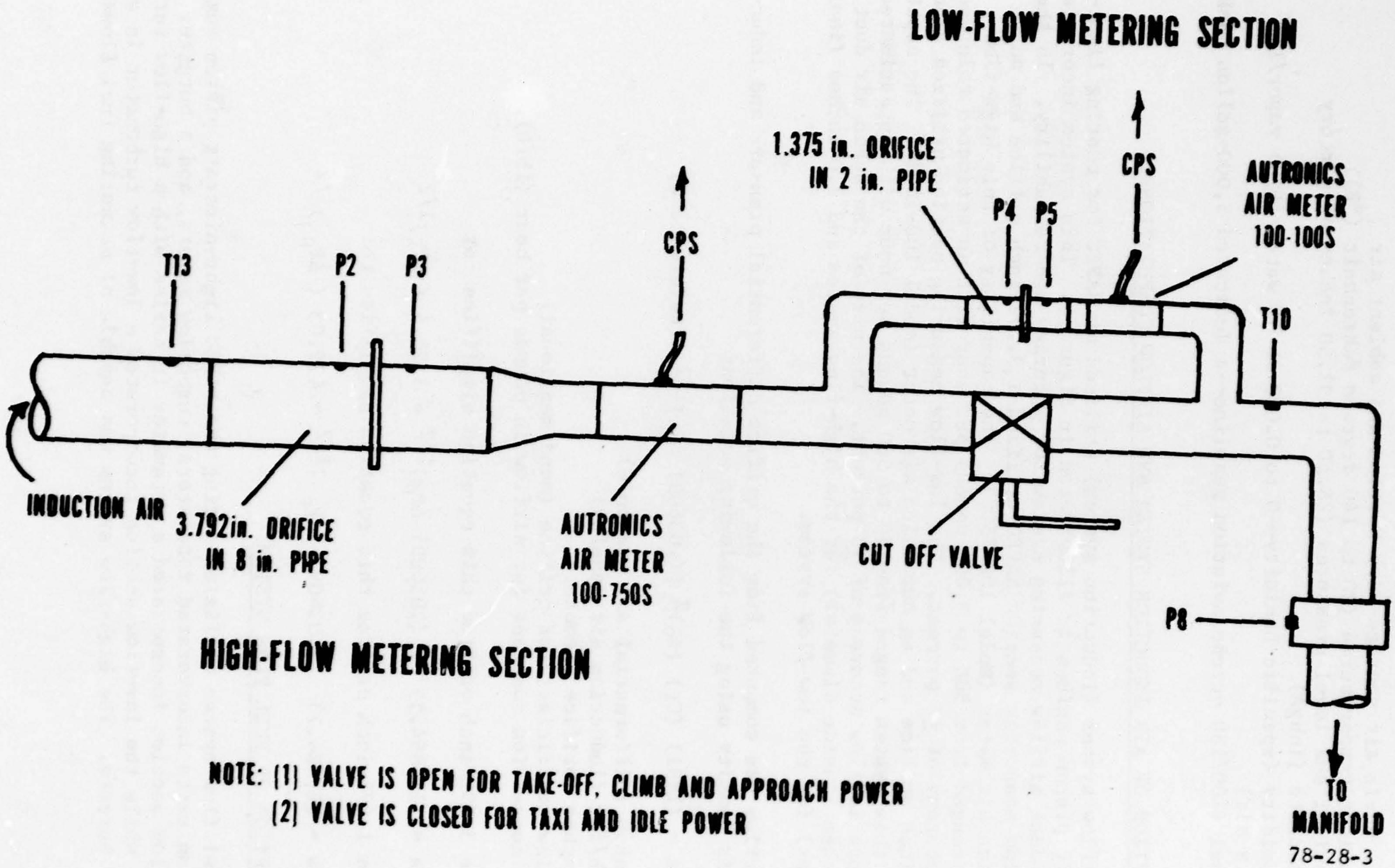


FIGURE 3. NAFEC AIR INDUCTION (AIRFLOW MEASUREMENT) SYSTEM FOR LIGHT-AIRCRAFT PISTON ENGINE EMISSION TESTS

50 lb/h up to 300 lb/h with an estimated tolerance of ±1.0 percent. The low-flow system was capable of flow measurements ranging from 0-50 lb/h with an estimated tolerance of ±2.0 percent. Figure 4 illustrates the NAFEC fuel flow system in schematic form.

DESCRIPTION OF COOLING AIR SYSTEM.

The NAFEC piston engine test facility also incorporated a system which provided cooling air (see figure 1) to the engine cylinders. The engine mounted in the test stand was enclosed in a simulated nacelle, and cooling air was provided to this enclosure from an external source. The cooling air temperature was maintained within ±10° F of the induction air supply temperature for any specified set of test conditions. This not only minimized variations in temperature but also minimized variations in the specific weight of air for all test conditions. All of the basic cooling air tests conducted with the 6-285-B engine (takeoff, climb, and approach modes (see appendix C)) were conducted with differential cooling air pressures of 3.0 inH_2O. During taxi mode tests, the cooling air differential pressure was approximately equal to 0 inH_2O.

DESCRIPTION OF TEST PROCEDURES AND EPA STANDARDS.

The data presented in this report were measured while conducting tests in accordance with specific landing and takeoff cycles (LTO) and by modal leanout tests. The basic EPA LTO cycle is defined in table 2.

The FAA/NAFEC contract and in-house test programs utilized an LTO cycle which was a modification of the table 2 test cycle. Table 3 defines this modified LTO cycle which was used to evaluate the total full rich emission characteristics of light aircraft piston engines.

TABLE 2. EPA FIVE-MODE LTO CYCLE

Mode No.	Mode Name	Time-In-Mode (Min.)	Power (%)	Engine Speed (%)
1	Taxi/idle (out)	12.0	*	*
2	Takeoff	0.3	100	100
3	Climb	5.0	75-100	*
4	Approach	6.0	40	*
5	Taxi/idle (in)	4.0	*	*

*Manufacturer's Recommended

TABLE 3. FAA/NAFEC SEVEN-MODE LTO CYCLE

Mode No.	Mode Name	Time-In-Mode (Min.)	Power (%)	Engine Speed (%)
1	Idle (out)	1.0	*	*
2	Taxi (out)	11.0	*	*
3	Takeoff	0.3	100	100
4	Climb	5.0	80	*
5	Approach	6.0	40	*
6	Taxi (in)	3.0	*	*
7	Idle (in)	1.0	*	*

*Manufacturer's Recommended

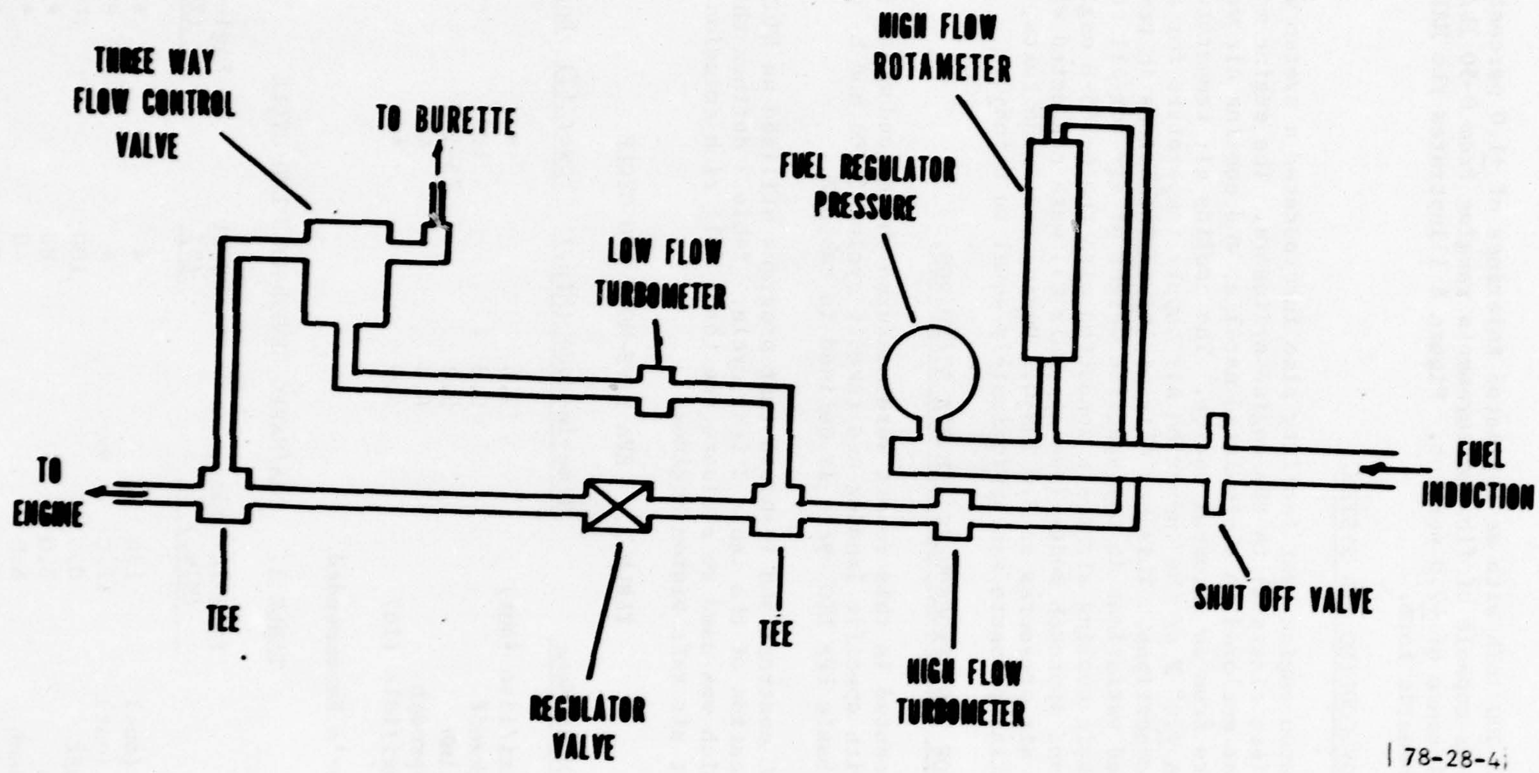


FIGURE 4. NAFEC FUEL FLOW SYSTEM FOR LIGHT-AIRCRAFT PISTON ENGINE EMISSION TESTS

An additional assessment of the test data clearly indicates that further evaluations of the general aviation piston exhaust emission must be analyzed with the climb mode emissions at 100-percent and 75-percent power setting (tables 4 and 5). This would then provide the basis for a complete evaluation of test data and permit a total assessment of the proposed EPA standard based on LTO cyclic tolerances.

TABLE 4. MAXIMUM FIVE-MODE LTO CYCLE

Mode No.	Mode Name	Time-In-Mode (Min.)	Power (%)	Engine Speed (%)
1	Taxi (out)	12.0	*	*
2	Takeoff	0.3	100	100
3	Climb	5.0	100	100
4	Approach	6.0	40	*
5	Taxi (in)	4.0	*	*

*Manufacturer's Recommended

TABLE 5. MINIMUM FIVE-MODE LTO CYCLE

Mode No.	Mode Name	Time-In-Mode (Min)	Power (%)	Engine Speed (%)
1	Taxi (out)	12.0	*	*
2	Takeoff	0.3	100	100
3	Climb	5.0	75	*
4	Approach	6.0	40	*
5	Taxi (in)	4.0	*	*

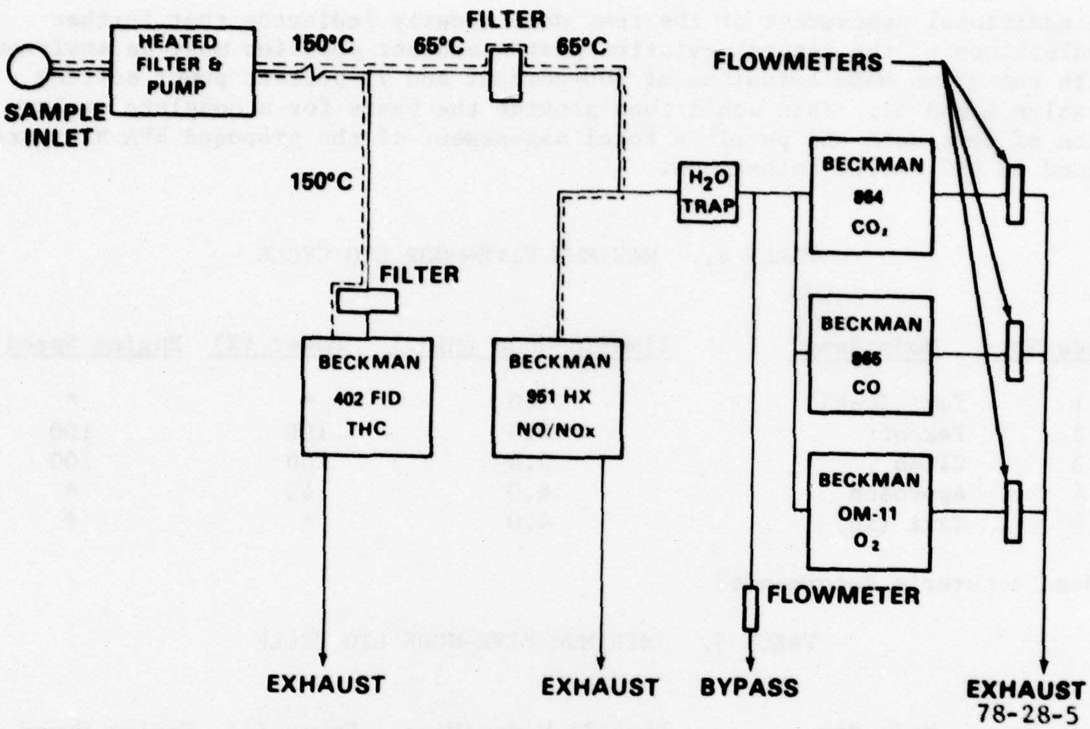
*Manufacturer's Recommended

The EPA Standards (reference 1) that were evaluated during this program were:

Carbon Monixide (CO)--0.042 lb/cycle/rated BHP
Unburned Hydrocarbon (HC)--0.0019 lb/cycle/rated BHP
Oxides of Nitrogen (NO_x)--0.0015 lb/cycle/rated BHP

DESCRIPTION OF EMISSIONS MEASUREMENT SYSTEM (Reference 3).

EMISSION ANALYZERS. The instrumentation used to monitor the exhaust emissions from general aviation piston engines was basically the same as that recommended by EPA, but with a number of modifications and additions to enhance the reliability and accuracy of the system. A schematic of the emissions measurement system is shown in figure 5.



- **CARBON DIOXIDE – CO_2**
  - NONDISPERSIVE INFRARED (NDIR)
  - RANGE 0-20%
  - REPEATABILITY ± 0.2% CO_2
- **CARBON MONOXIDE – CO**
  - NDIR
  - RANGE 0-20%
  - REPEATABILITY ± 0.2% CO
- **TOTAL HYDROCARBONS – THC**
  - FLAME IONIZATION DETECTOR (FID)
  - RANGE 0-150,000 ppm_c
  - MINIMUM SENSITIVITY 1.5 ppm_c
  - LINEAR TO 150,000 ppm_c
- **OXIDES OF NITROGEN – NO_X**
  - CHEMILUMINESCENT (CL)
  - RANGE 0-10,000 ppm
  - MINIMUM SENSITIVITY 0.1 ppm
- **OXYGEN – O_2**
  - POLARAGRAPHIC
  - RANGE 0-100%
  - REPEATABILITY 0.1% O_2
  - RESPONSE 200 ms

78-28-6

FIGURE 5. SCHEMATIC OF EMISSIONS MEASUREMENT SYSTEMS AND MEASUREMENT CHARACTERISTICS

EMISSION INSTRUMENTATION ACCURACY/MODIFICATION. The basic analysis instrumentation utilized for this system is explained in the following paragraphs.

Carbon Dioxide. The carbon dioxide (CO_2) subsystem is constructed around a Beckman model 864-23-2-4 nondispersive infrared analyzer (NDIR). This analyzer has a specified repeatability of ±1 percent of full scale for each operating range. The calibration ranges on this particular unit are: Range 1, 0 to 20 percent; Range 3, 0 to 5 percent. Stated accuracy for each range is, ±0.2 and ±0.05 percent, respectively.

Carbon Monoxide. The subsystem used to measure carbon monoxide (CO) is constructed around a Beckman model 865-X-4-4-4 NDIR. This analyzer has a specified repeatability of ±1 percent of full scale for ranges 1 and 2 and ±2 percent of full scale for range 3.

Range 1 has been calibrated for 0 to 20 percent by volume, range 2 for 0 to 1,000 parts per million (ppm) and range 3 for 0 to 100 ppm. The wide-range capability of this analyzer is made possible by using stacked sample cells which in effect give this analyzer six usable ranges when completely calibrated.

Effects of interfering gases, such as CO_2 and water vapor, were determined and reported by the factory. Interferences from 10 percent CO_2 were determined to be 12 ppm equivalent CO, and interferences from 4 percent water vapor were determined to be 6 ppm CO equivalent. Even though the interference from water vapor is negligible, a condenser is used in the CO/CO_2 subsystem to eliminate condensed water in the lines, analyzers, and flowmeters. This condensation would have decreased analyzer sensitivity and necessitated more frequent maintenance if it had been eliminated.

Total Hydrocarbons. The system that is used to measure total hydrocarbons is a modified Beckman model 402 heated flame ionization detector. This analyzer has a full-scale sensitivity that is adjustable to 150,000 ppm carbon with intermediate range multipliers 0.5, 0.1, 0.05, 0.01, 0.005, and 0.001 times full scale.

Repeatability for this analyzer is specified to be ±1 percent of full scale for each range. In addition, this modified analyzer is linear to the full-scale limit of 150,000 ppm carbon when properly adjusted. The two major modifications which were made to this analyzer were the installation of a very fine metering value in the sample capillary tube, and the installation of an accurate pressure transducer and digital readout to monitor sample pressure. Both of these modifications were necessary because of the extreme pressure sensitivity of the analyzer (figures 6 through 8). Correct instrument response depends on the amount of sample passing through a capillary tube; as a result, if there is too high a sample flow, the analyzer response becomes nonlinear when a high concentration gas is encountered. Sample flow may be controlled by varying the pressure on this capillary or increasing the length of the capillary. On this analyzer, linearity to 50,000-ppm carbon was obtained by reducing the sample pressure to 1.5 pounds per square inch gauge (psig). However, the need

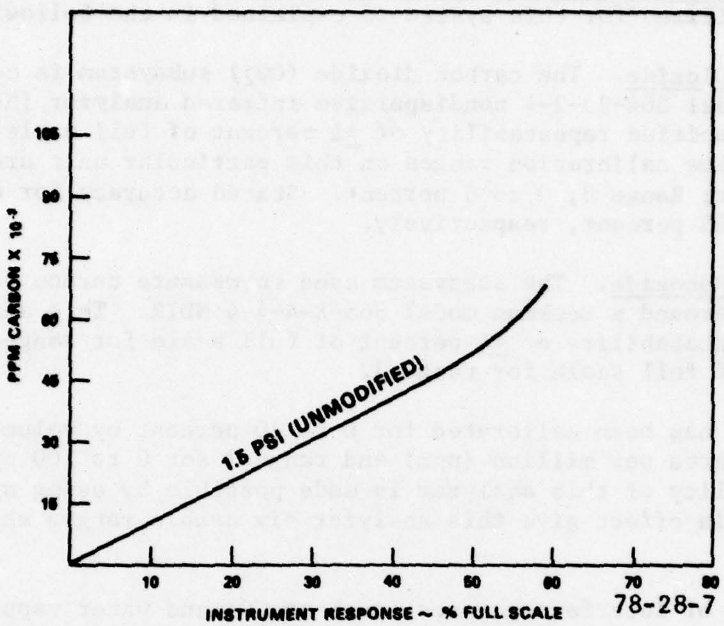


FIGURE 6. BECKMAN MODEL 402 THC ANALYZER 1.5 PSI UNMODIFIED)

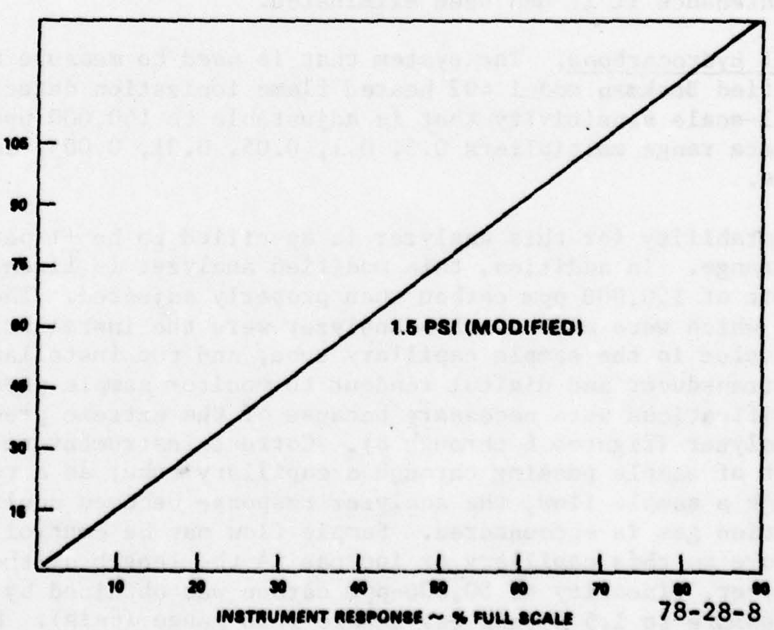


FIGURE 7. BECKMAN MODEL 402 THC ANALYZER (1.5 PSI MODIFIED)

for linearity to 120,000-ppm carbon was anticipated. Further reduction of the sample pressure increased the noise level of the analyzer to an unacceptable level. In order to reduce the flow through the capillary without using a lower pressure, either the length or the resistance of the capillary had to be increased. The standard modification for this analyzer in order to limit flow is the installation of an additional length of capillary tubing. This procedure requires trial and error determination of proper capillary length and is a permanent modification that limits sensitivity at low hydrocarbon levels. By installing a metering valve in the capillary, flow could be selectively set at either low flow for linearity at high concentrations or high flow for greater sensitivity at low concentrations. Installation time was reduced by eliminating the cut-and-try procedure for determining capillary length.

The addition of a sensitive pressure transducer and digital readout to monitor sample pressure was needed since the pressure regulator and gauge supplied with the analyzer would not maintain the pressure setting accurately at low pressures. Using the digital pressure readout, the sample pressure could be monitored and easily maintained to within 0.05 inH_2O.

Oxides of Nitrogen. Oxides of nitrogen (NO_x) are measured by a modified Beckman model 951H atmospheric pressure, heated, chemiluminescent analyzer (CL). This analyzer has a full-scale range of 10,000 ppm with six intermediate ranges. Nominal minimum sensitivity is 0.1 ppm on the 10 ppm full-scale range.

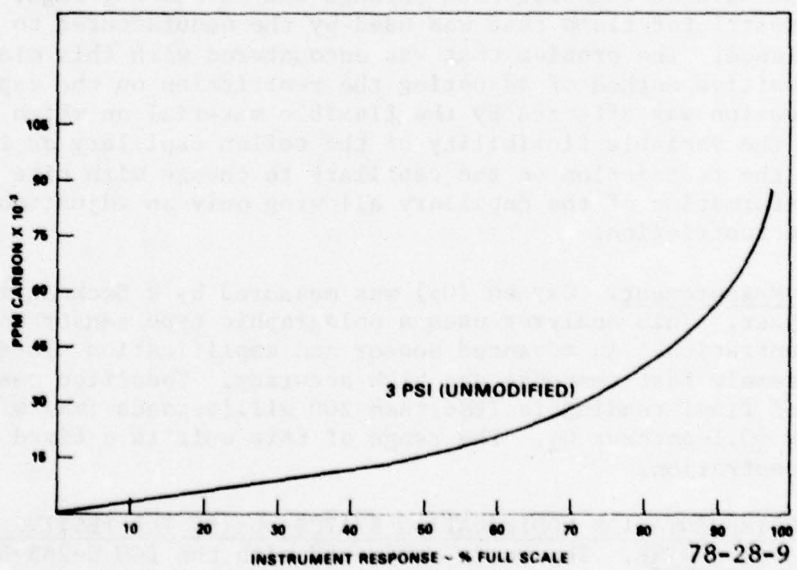


FIGURE 8. BECKMAN MODEL 402 THC ANALYZER (3PSI UNMODIFIED)

The atmospheric pressure analyzer was chosen because of its simplicity, ease of maintenance, and compactness. Anticipated water vapor problems in the atmospheric pressure unit were to be handled by the heating of the internal sample train. Interference from CO_2 quenching, common in the atmospheric pressure type CL analyzer, was checked and found to be nonexistent.

A series of major modifications were performed by the manufacturer on this analyzer to insure compliance with specifications. One such modification was installed in order to maintain the temperature of the sample stream above the dew point of the sample gas. Originally this analyzer was specified to maintain a temperature of 140° F at all points in contact with the sample. After a survey of the 951H analyzers in use on FAA projects, it was determined that this temperature was not being achieved because the method used to heat the components was inadequate. A recommendation was made to the manufacturer to install a positive method of heating the sample tube compartment and reaction chamber that would be thermostatically controlled. In time, the modification was made, and this problem was eliminated. Increasing the temperature of the internal sample components eliminated the condensed water problem; however, the elevated temperature caused an instability in the photomultiplier tube output. Another recommendation was made to thermostatically control the temperature of this tube. This was accomplished by installing an electronic cooling jacket designed to maintain the photomultiplier tube at a constant temperature below the internal case temperature.

A further modification required was the addition of a flow control valve to adjust and balance the flow rate through the NO and NO_x legs. This valve replaced a restrictor clamp that was used by the manufacturer to set the NO to NO_x flow balance. The problem that was encountered with this clamp was that it was not a positive method of adjusting the restriction on the capillary. The clamp compression was affected by the flexible material on which the clamp was mounted and the variable flexibility of the teflon capillary as it was heated. This caused the restriction on the capillary to change with time and caused permanent deformation of the capillary allowing only an adjustment that would increase the restriction.

Oxygen Measurement. Oxygen (O_2) was measured by a Beckman model OM-11 oxygen analyzer. This analyzer uses a polagraphic type sensor unit to measure oxygen concentration. An advanced sensor and amplification system combine to give an extremely fast response and high accuracy. Specified response for 90 percent of final reading is less than 200 milliseconds (ms) with an accuracy of less than $\pm$0.1-percent O_2. The range of this unit is a fixed 0 to 100 percent O_2 concentration.

EMISSIONS INSTRUMENTATION MODIFICATION STATUS DURING THE TESTING OF THE 6-285-B (TIARA) ENGINE. The tests conducted with the TCM 6-285-B (TIARA) engine utilized all of the above noted instrumentation and the latest modifications to this instrumentation. The OM-11 O_2 analyzer and the latest prototype 951H NO_x analyzer were both in use.

All of the emissions and exhaust constituent-measuring instruments/analyzers incorporated the latest specified modifications described in this report.

DESCRIPTION OF SAMPLE HANDLING SYSTEM.

Exhaust samples are transported to the analysis instrumentation under pressure through a 35-foot-long, 3/8-inch O.D., heated, stainless steel sample line. The gas is first filtered and then pumped through this line by a heated Metal Bellows model MB-158 high temperature stainless steel sample pump. The pump, filter, and line are maintained at a temperature of 300° $\pm$4° F to prevent condensation of water vapor and hydrocarbons. At the instrument console, the sample is split to feed the hydrocarbon, oxides of nitrogen, and $CO/CO_2/O_2$ subsystems which require different temperature conditioning. The sample gas to the total hydrocarbon subsystem is maintained at 300° F while the temperature of remaining sample gas to the NO_x and $CO/CO_2/O_2$ system is allowed to drop to 150° F. Gas routed to the oxides of nitrogen subsystem is then maintained at 150° F, while the gas to the $CO/CO_2/O_2$ subsystem is passed through a 32° F condenser to remove any water vapor present in the sample. Flow rates to each analyzer are controlled by a fine-metering valve and are maintained at predetermined values to minimize sample transport and system response time. Flow is monitored at the exhaust of each analyzer by three 15-centimeter (cm) rotameters. Two bypasses are incorporated into the system to keep sample transport time through the lines and condenser to a minimum without causing adverse pressure effects in the analyzers.

DESCRIPTION OF FILTRATION SYSTEM.

Particulates are removed from the sample at three locations in the system, thereby minimizing downtime due to contaminated sample lines and analyzers (figure 5). Upstream of the main sample pump is a heated clamshell-type stainless steel filter body fitted with a Whatman GF/C glass fiber paper filter element capable of retaining particles in the 0.1 micron range. A similar filter is located in the total hydrocarbon analyzer upstream of the sample capillary. A Mine Safety Appliances (MSA) type H ultra filter capable of retaining 0.3 micron particles is located at the inlet to the oxides of nitrogen and $CO/CO_2/O_2$ subsystems.

COMPUTATION PROCEDURES.

The calculations required to convert exhaust emission measurements into mass emissions are the subject of this section.

Exhaust emission tests were designed to measure CO_2, CO, unburned hydrocarbons (HC), NO_x, and exhaust excess O_2 concentrations in percent or ppm by volume. Mass emissions were determined through calculations utilizing the data obtained during the simulation of the aircraft LTO cycle and from modal lean-out data.

COMBUSTION EQUATION. The basic combustion equation can be expressed very simply:

Fuel + Air = Exhaust Constituents

An initial examination of the problem requires the following simplifying assumptions:

1. The fuel consists solely of compounds of carbon and hydrogen.

2. The air is a mixture of oxygen and inert nitrogen in the volumetric ratio of 3.764 parts apparent nitrogen to 1.0 part oxygen (see appendix B for additional details).

3. If a stoichiometric combustion process exists, the fuel and air are supplied in chemically correct proportions.

4. The fuel (which consists usually of a complex mixture of hydrocarbons) can be represented by a single hydrocarbon having the same carbon-hydrogen ratio and molecular weight as the fuel; usually C_8H_{17} as an average fuel.

Applying the above assumptions for stoichiometric conditions, a useful general reaction equation for hydrocarbon fuel is:

$$M_fC_8H_{17} + M_a\ (O_2 + 3.764N_2 + M_wH_2O) \rightarrow M_1CO_2 + M_3H_2O + M_5N_2 \qquad (1)$$

(References 4 and 5)

Where
M_f = Moles of Fuel
M_a = Moles of Air or Oxygen
M_1 = Moles of Carbon Dioxide (CO_2)
M_3 = Moles of Condensed Water (H_2O)
M_5 = Moles of Nitrogen (N_2) - Exhaust
$3.764M_a$ = Moles of Nitrogen (N_2) - In Air
M_aM_w = Moles of Humidity (H_2O) - In Air

The above equation is applicable to dry air when M_w is equal to zero.

From equation (1), and assuming dry air with one mole of fuel (M_f=1.0), the stoichiometric fuel-air ratio may be expressed as:

$$(F/A)_s = \frac{\text{Wt. Fuel}}{\text{Wt. Air Required}} = \frac{12.011\ (8) + 1.008\ (17)}{12.25\quad 32.000 + 3.764(28.161)} \qquad (2)$$

$$(F/A)_s = \frac{113.224}{12.25(137.998)} = 0.067$$

The mass carbon-hydrogen ratio of the fuel may be expressed as follows:

$$C/H = \frac{12.001(8)}{1.008(17)} = \frac{96.088}{17.136} = 5.607 \qquad (3)$$

The atomic hydrogen-carbon ratio is:

$$17/8 = 2.125 \qquad (4)$$

The stoichiometric fuel-air ratio may be expressed as a function of the mass carbon-hydrogen ratio of the fuel. The derivation of this equation is presented in reference 4.

$$(F/A)_s = \frac{C/H + 1}{11.5(C/H+3)} \tag{5}$$

$(F/A)_s = 0.067$ for a mass carbon-hydrogen ratio of 5.607

With rich (excess fuel) mixtures, which are typical for general aviation piston engines, some of the chemical energy will not be liberated because there is not enough air to permit complete oxidation of the fuel. Combustion under such conditions is an involved process. By making certain simplifying assumptions based on test results, the effect of rich mixtures may be calculated with reasonable accuracy.

For rich (excess fuel) mixtures, equation (1) will now be rewritten to express the effects of incomplete combustion:

$$M_fC_8H_{17} + M_a(O_2 + 3.764N_2 + M_wH_2O) \rightarrow M_1CO_2 + M_2CO + M_3H_2O + M_4H_2 +$$

$$M_5N_2 + M_6NO + M_7CH_4 + M_8O_2 + M_9C \tag{6}$$

Since only a limited number of the exhaust constituents were measured during the testing of general aviation piston engines, the above equation can only be solved by applying certain expeditious assumptions and empirical data.

An important requirement was the accurate measurement of air and fuel flows. These parameters provide the data for determining engine mass flow (W_m), and with the aid of figure 9 (developed from reference 6), it is a simple computation to calculate the total moles (M_{tp}) of exhaust products being expelled by general aviation piston engines.

$$(M_{tp}) = W_m \text{ (engine mass flow)} \div \text{(exh. mol. wt)} \tag{7}$$

Since the unburned hydrocarbons (HC) and oxides of nitrogen (NO_x) are measured wet, it becomes a very simple matter to compute the moles of HC and NO_x that are produced by light-aircraft piston engines.

$$M_7 \text{ (Moles of HC)} = (\text{ppm} \div 10^6) \times M_{tp} \tag{8}$$

$$M_6 \text{ (Moles of } NO_x) = (\text{ppm} \div 10^6) \times M_{tp} \tag{9}$$

If the dry products (M_{dp}) of combustion are separated from the total exhaust products (M_{tp}), it is possible to develop a partial solution for five of the products specified in equation 6.

This can be accomplished as follows:

The summation of the mole fractions $(MF)_d$ for dry products is

$$m_1 + m_2 + m_4 + m_5 + m_8 = 1.0000 \tag{10}$$

$m_1 = MF(CO_2) = \%CO_2$ (measured dry), expressed as a fraction

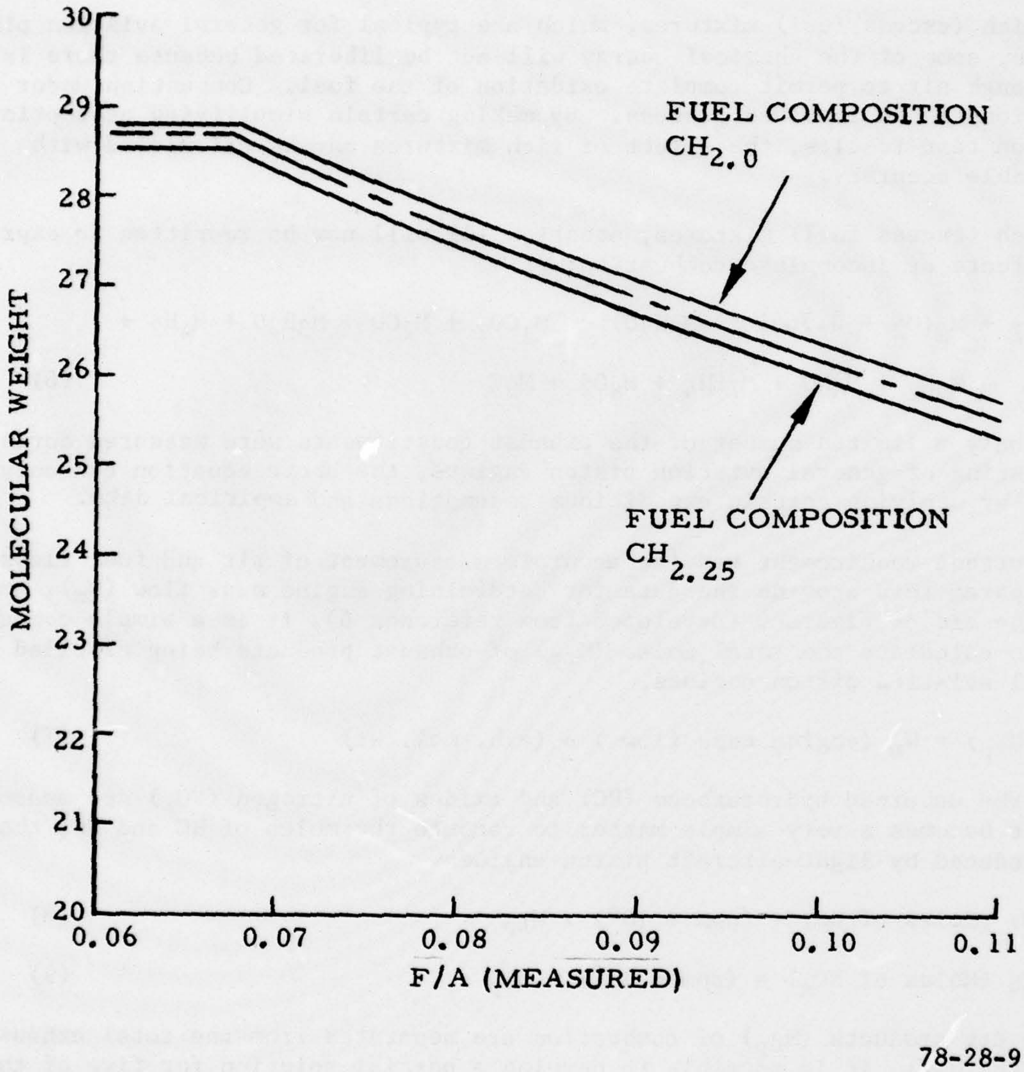


FIGURE 9. EXHAUST GAS MOLECULAR WEIGHTS

$m_2 = MF(CO) = \%CO$ (measured dry), expressed as a fraction

$m_4 = MF(H_2) = K_4\ (\%CO)$ (see figure 10, also references 5, 6, and 7), expressed as a fraction

$m_8 = MF(O_2) = \%O_2$ (measured dry), expressed as a fraction

$$m_5 = 1.0000 - (m_1 + m_2 + m_4 + m_8) = \%N_2 \text{ (dry), expressed as a fraction} \quad (11)$$

Utilizing the nitrogen balance equation, it is now possible to determine the moles of nitrogen that are being exhausted from the engine.

$$M_5 = 3.764M_a - (M_6 \div 2);\ M_6 = \text{moles (NO)} \quad (12)$$

The moles of exhaust dry products (M_{dp}) may now be determined by dividing equation 12 by equation 11.

$$M_{dp} = M_5 \div m_5 \quad (13)$$

Using all the information available from equations (7), (8), (9), (10), (11), (12), and (13), it is now possible to determine the molar quantities for seven exhaust products specified in equation 6.

$$\text{Moles } (CO_2) = M_1 = m_1 \times M_{dp} \quad (14)$$

$$\text{Moles } (CO) = M_2 = m_2 \times M_{dp} \quad (15)$$

$$\text{Moles } (H_2) = M_4 = m_4 \times M_{dp} \quad (16)$$

$$\text{Moles } (N_2) = M_5 = m_5 \times M_{dp} \quad (17)$$

$$\text{Moles } (O_2) = M_8 = m_8 \times M_{dp} \quad (18)$$

$$\text{Moles } (CH_4) = M_7 = (\text{ppm} \div 10^6) \times M_{tp} \quad (19)$$

$$\text{Moles } (NO) = M_6 = (\text{ppm} \div 10^6) \times M_{tp} \quad (20)$$

To determine M_3 (moles of condensed H_2O), it is now appropriate to apply the oxygen balance equation.

$$M_3 = M_a\ (2 + M_w) - (2M_1 + M_2 + M_6 + 2M_8) = \text{Moles } (H_2O) \quad (21)$$

The remaining constituent specified in equation 6 may now be determined from the carbon balance equation 22.

$$M_9 = 8M_f - (M_1 + M_2 + M_7) \quad (22)$$

A check for the total number of exhaust moles (M_{tp}), calculated from equation 9, may now be determined from equation 23.

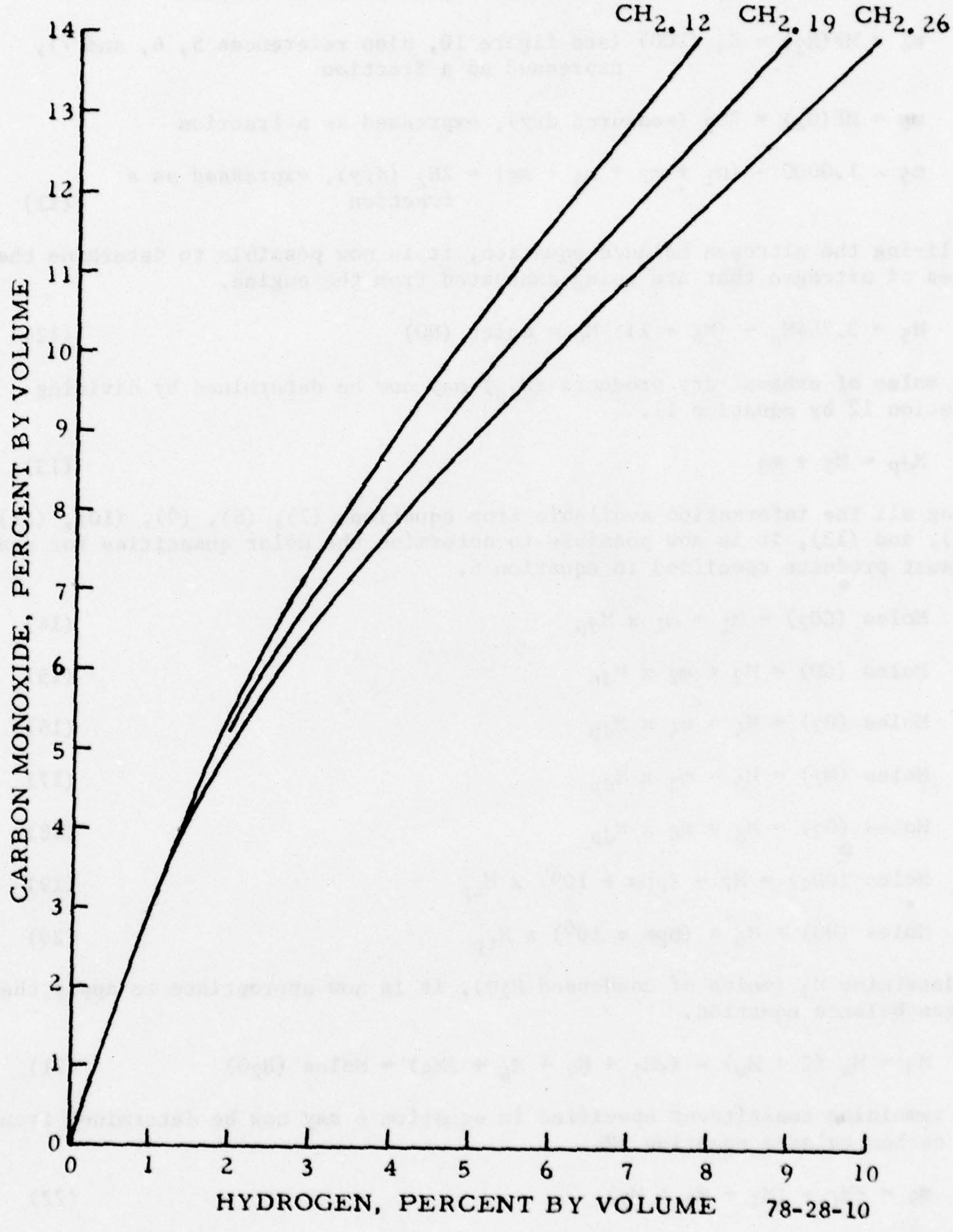


FIGURE 10. RELATION OF CARBON MONOXIDE AND HYDROGEN

$$M_{tp} = M_1 + M_2 + M_3 + M_4 + M_5 + M_6 + M_7 + M_8 + M_9 \quad (23)$$

$$\dot{m}_1 + \dot{m}_2 + \dot{m}_3 + \dot{m}_4 + \dot{m}_5 + \dot{m}_6 + \dot{m}_7 + \dot{m}_8 + \dot{m}_9 = 1.0000 \quad (24)$$

$$\dot{m}_1 = MF(CO_2) = M_1 \div M_{tp}$$

$$\dot{m}_2 = MF(CO) = M_2 \div M_{tp}$$

$$\dot{m}_3 = MF(H_2O) = M_3 \div M_{tp}$$

$$\dot{m}_4 = MH(H_2) = M_4 \div M_{tp}$$

$$\dot{m}_5 = MF(N_2) = M_5 \div M_{tp}$$

$$\dot{m}_6 = MH(NO) = M_6 \div M_{tp}$$

$$\dot{m}_7 = MF(CH4) = M_7 \div M_{tp}$$

$$\dot{m}_8 = MF(O_2) = M_8 \div M_{tp}$$

$$\dot{m}_9 = MF(C) = M_9 \div M_{tp}$$

The exhaust constituent mass flow rates may be computed in the following manner using each exhaust constituents molar constant with the appropriate molecular weight.

$$M_1 \times 44.011 = CO_2 \text{ in lb/h} \quad (25)$$

$$M_2 \times 28.011 = CO \text{ in lb/h} \quad (26)$$

$$M_3 \times 18.016 = H_2O \text{ in lb/h} \quad (27)$$

$$M_4 \times 2.016 = H_2 \text{ in lb/h} \quad (28)$$

$$M_5 \times 28.161 = N_2 \text{ in lb/h} \quad (29)$$

$$M_6 \times 30.008 = NO \text{ in lb/h} \quad (30)$$

$$M_7 \times 16.043 = CH_4 \text{ in lb/h} \quad (31)$$

$$M_8 \times 32.000 = O_2 \text{ in lb/h} \quad (32)$$

$$M_9 \times 12.011 = C \text{ in lb/h} \quad (33)$$

The exhaust fuel flow (W_{fe}), based on exhaust constituents, can now be calculated on a constituent-by-constituent basis as follows:

$$(M_1 + M_2 + M_9) \times 12.011 = \text{lb/h} \quad (34)$$

$$M_7 \times 16.043 = \text{lb/h} \quad (35)$$

$(M_3 - M_a M_w) + M_4 \times 2.016 = lb/h$ (36)

$W_{fe} = (34) + (35) + (36) = lb/h$ (37)

In a similar manner the exhaust airflow (W_{ae}) can also be calculated on a constituent-by-constituent basis:

$M_1 \times 32.000 = lb/h$ (38)

$M_2 \times 16.000 = lb/h$ (39)

$(M_3 \times 16.000) + (M_a M_w \times 18.016) = lb/h$ (40)

$M_5 \times 28.161 = lb/h$ (41)

$M_6 \times 30.008 = lb/h$ (42)

$M_8 \times 32.000 = lb/h$ (43)

$W_{ae} = \Sigma(38) \leftrightarrow (43) = lb/h$ (44)

Using equations (37) and (44) it is now possible to determine a calculated fuel-air ratio on the basis of total exhaust constituents.

$(F/A)_{calculated} = (37) \div (44)$ (45)

RESULTS

GENERAL COMMENTS.

General aviation piston engine emission tests were conducted to provide the following categories of data:

1. Full-rich (or production fuel schedule) baseline data for each power mode specified in the LTO test cycle.

2. Lean-out data for each power mode specified in the LTO test cycle.

3. Data for the above categories at different spark settings.

4. Data for each power mode specified in the LTO test cycle utilized cooling air flow $\Delta P = 3.0$ inH_2O at takeoff, climb, and approach powers.

RESULTS OF BASELINE TESTS (LANDING-TAKEOFF CYCLE EFFECTS).

Based on an analysis of the factors affecting piston engine emissions (time in mode, F/A, ambient conditions, etc.), it can be shown that the mode conditions

having the greatest influence on the gross pollutant levels produced by the combustion process are taxi, approach, and climb when using the LTO cycle defined in tables 3, 4, and 5. The five-mode LTO cycle shows that approximately 99 percent of the total cycle time (27.3-min) is attributed to these three modal conditions. Furthermore, the taxi modes (both out and in) account for slightly less than 59 percent of the total cycle time. The remainder of the time is almost equally apportioned to the approach and climb modes (22 and 18 percent, respectively).

As a result of these time apportionments, it was decided that an investigation and evaluation of the data should be undertaken to determine which mode(s) has the greatest influence on improving general aviation piston engine emissions. The subsequent sections of this report will show the exhaust emissions characteristics for a TCM 6-285-B engine (S/N700106) and what improvements are technically feasible within the limits of safe aircraft/engine operational requirements based on sea level propeller test stand evaluations conducted at NAFEC.

The first set of data to be presented and evaluated are the five-mode baseline runs conducted to establish the current production full-rich exhaust emissions characteristics of the 6-285-B engine. These are summarized in tabular form in appendix C (see tables C-1 through C-10) and includes data that were obtained for a range of sea level ambient conditions, specified as follows:

Induction air temperature (T_i)	= 60° F to 130° F
Cooling air temperature (T_c)	= $T_i \pm 10$° F
Induction air pressure (P_i)	= 28.50 to 30.50 inHgA
Induction air density (ρ_i)	= 0.0670 to 0.0785 lb/ft^3

Figure 11 presents five-mode baseline data in bargraph form (for different sea level ambient conditions). It also compares the total emissions characteristics of the 6-285-B engine (current production configuration) with the proposed EPA standards as a function of percent of standard. The data that were utilized to develop figure 11 is tabulated in appendix C and plotted in various forms for analysis and evaluation in figures C-1 through C-19. Tables C-19 through C-21 provide the data tabulation that was used to construct the bargraphs for T_i=60° F, 80° F, and 100° F.

RESULTS OF LEAN-OUT TESTS.

In the subsequent sections of this report, it will be shown what improvements can be achieved as a result of making lean-out adjustments to the fuel metering device: (1) taxi mode only, (2) taxi and approach modes combined, and (3) leaning-out the climb mode to "best power" in combination with taxi and approach mode leaning.

EFFECTS OF LEANING-OUT ON CO EMISSIONS. The test data obtained as a result of NAFEC testing the TCM 6-285-B (TIARA) have been evaluated on the basis of leaning-out the taxi, approach, and climb modes while continuing the operation of the test engine at the production rich and lean limits in the takeoff mode. The results of leaning-out under this procedure are shown in bargraph form in figure 12.

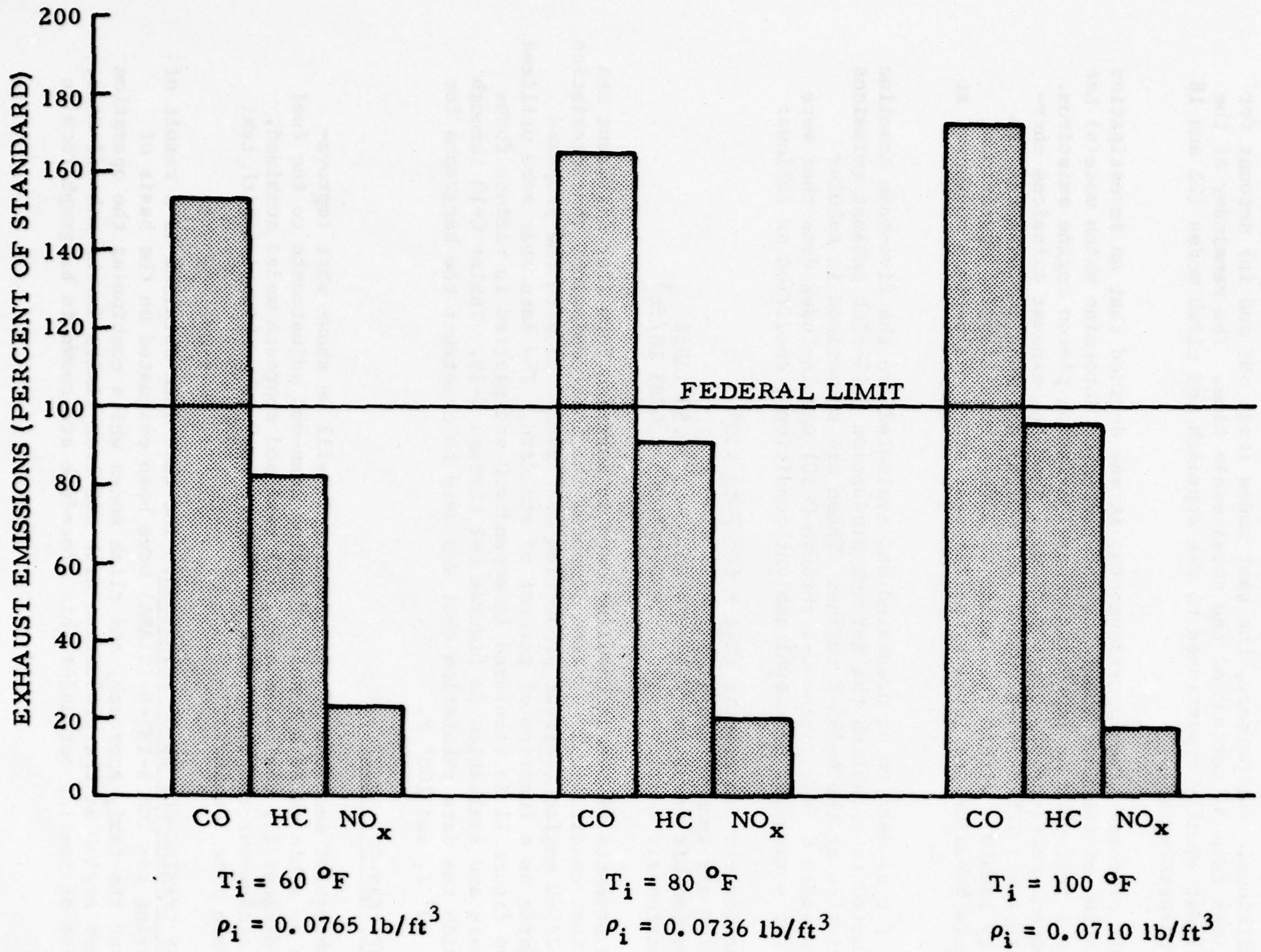


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FIGURE 11. TOTAL EMISSIONS CHARACTERISTICS FOR A TCM 6-285-B (TIARA) ENGINE OPERATING UNDER VARYING SEA LEVEL INDUCTION AIR TEMPERATURES--PRODUCTION RICH LIMIT

NOTES:
1. THIS FIGURE IS BASED ON THE TABLE 5 LTO CYCLE WITH THE CLIMB MODE AT APPROXIMATELY 80 PERCENT POWER.
2. THE MINIMUM F/A RATIO SETTINGS FOR THIS FIGURE ARE 0.0705 FOR THE APPROACH MODE AND 0.075 FOR THE TAXI MODE; TAKEOFF WAS SET FOR A FUEL FLOW OF 160 lb/h AND CLIMB WAS SET TO BEST POWER - - THESE SETTINGS APPLY TO THE LOWEST BARGRAPH GROUP.

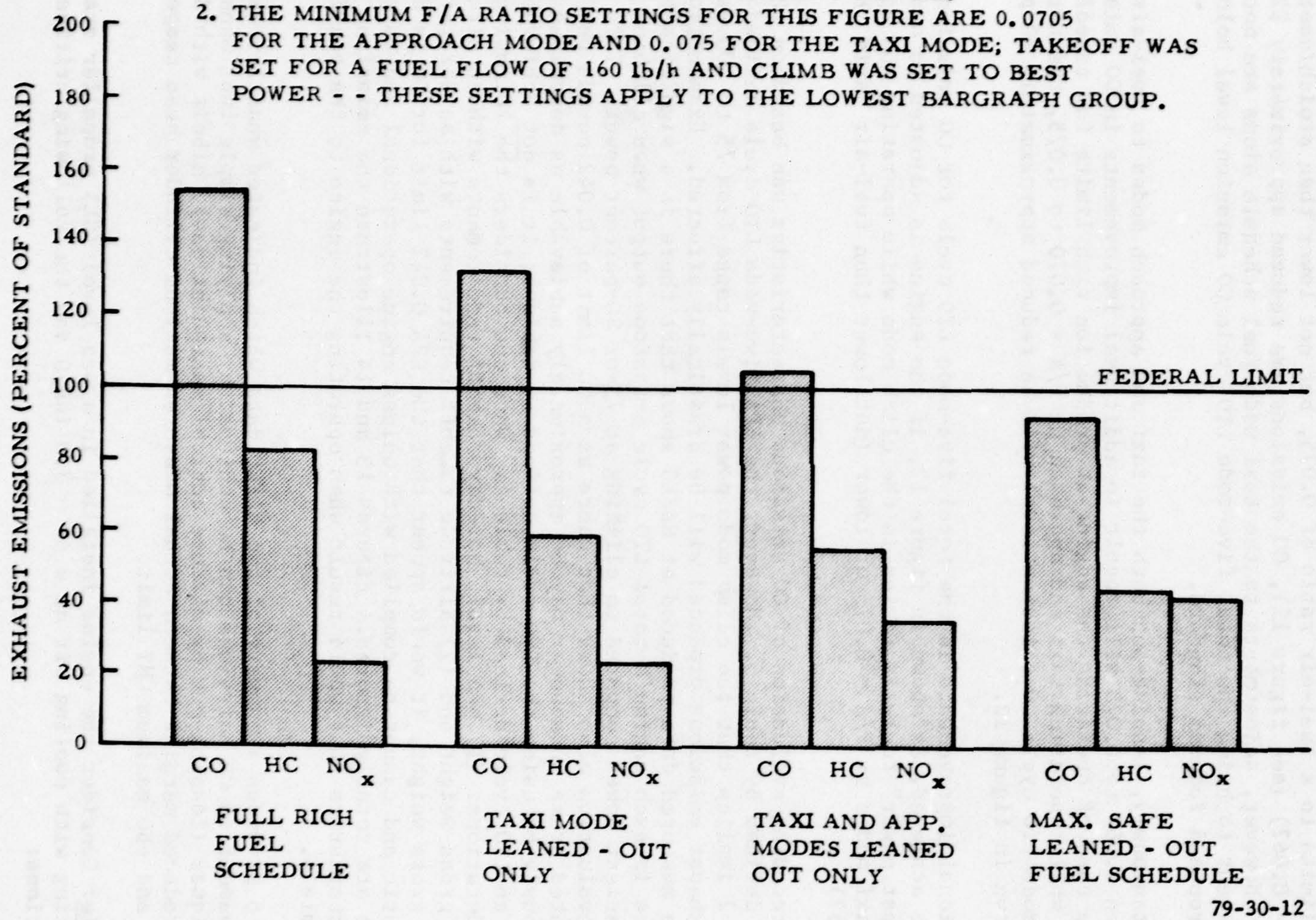

FIGURE 12. TOTAL EMISSIONS CHARACTERISTICS FOR A TCM 6-285-B (TIARA) ADJUSTMENTS--SEA LEVEL STANDARD DAY

When the taxi modes (out and in) are leaned-out from the production rich or lean limits to a fuel-air ratio of 0.075, but not lower than stoichiometric (F/A = 0.067) (see figure 12), CO emissions are reduced approximately 22 percent. However, adjustments to the taxi mode fuel schedule alone are not sufficient to bring the total five-mode LTO cycle CO emission level below the proposed federal standard.

Simultaneously, leaning-out both the taxi and approach modes to fuel-air ratios between 0.067 to 0.075 will result in additional improvements in CO emissions. In the case of operating the engine at production rich limits for takeoff and climb while operating taxi and approach at F/A = 0.070 to 0.075, the total five-mode LTO cycle CO emission level will be reduced approximately 50 percent as shown in figure 12.

Additional improvements in the total five-mode LTO cycle for CO emissions can be achieved, as shown in figure 12, if the engine is adjusted to operate at "best power" fuel-air ratios in the climb mode while operating the approach and taxi modes at F/A = 0.075 or lower (not lower than fuel-air ratio (F/A) = 0.067).

The preceding evaluation of CO emissions characteristics was based on the LTO cycle defined by table 5. However, the EPA five-mode LTO cycle defined by table 2 implies that the climb mode power levels range from 75 to 100 percent. The exhaust emissions produced will be drastically affected. Examination of the measured data produced at NAFEC shows that there is a significant difference in each engine's total LTO cycle emissions output when climbing at 100 percent power compared to climbing at 75-or 80-percent power. This data evaluation also shows that where as a CO limit of 0.042 pounds per cycle per rated brake horsepower may be approximately achievable as described previously by using the LTO cycle defined by table 5; it is <u>not</u> achievable using an LTO cycle defined by table 4. When one considers the following safety considerations: (1) sea level, hot-day takeoff requirements with an aircraft at heavy gross weight and (2) altitude takeoff requirements with an aircraft at heavy gross weight, it would appear that the EPA 0.042 limit for CO is not realistic and cannot be complied with unless engine operational and safety limits are totally ignored. Figures 13 and 14 illustrate the emissions characteristics that would result when operating the engine to the requirements of table 4.

Table 6 provides a summary of the NAFEC data which indicates what levels of improvement in CO emissions can be achieved by applying simple fuel management techniques (leaning-out by mixture control manipulations), albeit with drastically reduced margins between actual measured maximum cylinder head temperature (CHT) and the maximum CHT limit.

<u>Example</u>: Consider the engine installed in a sea level (SL) propeller stand and operating with cooling air at a $\Delta P = 3.0$ inH_2O and the following critical test conditions:

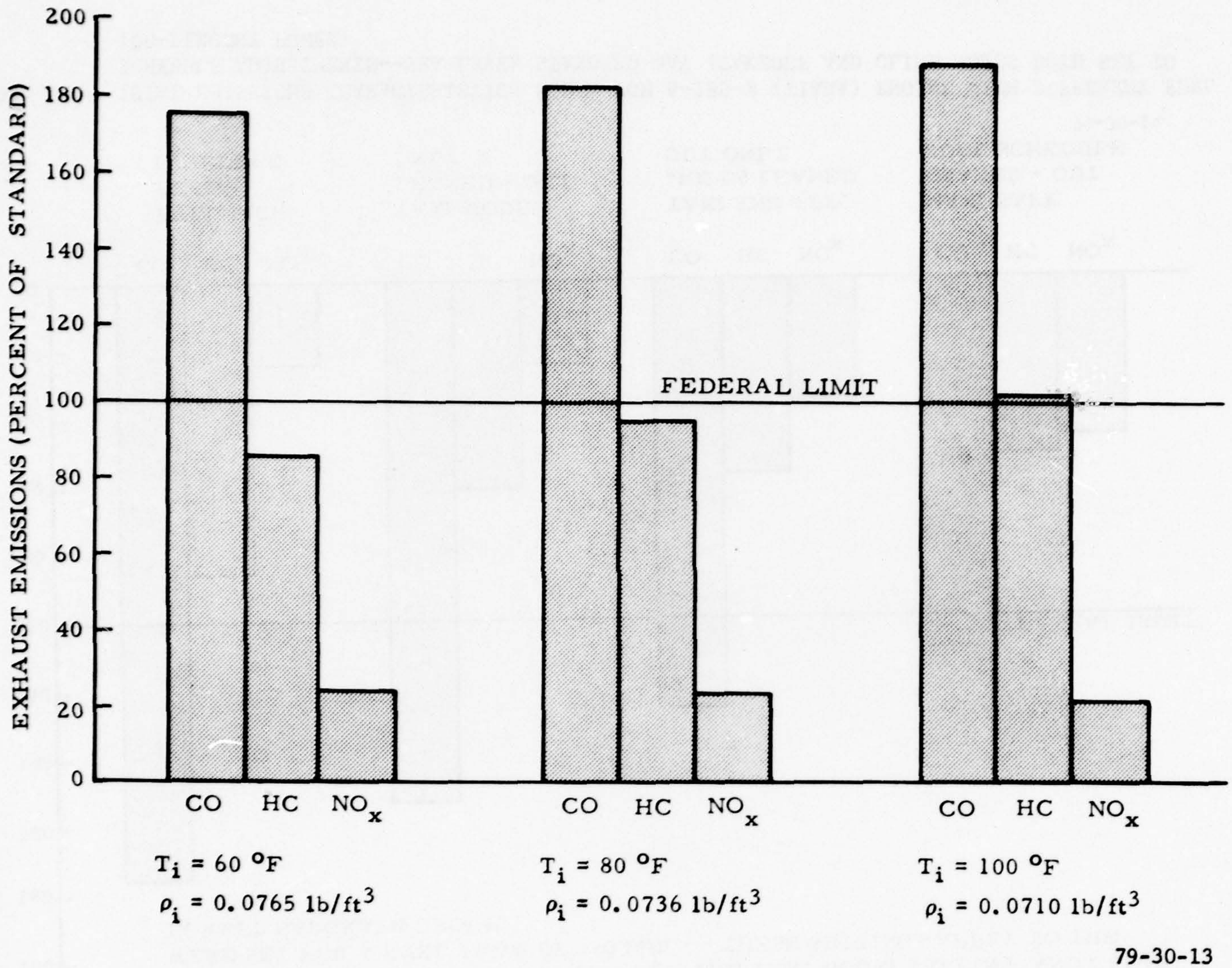

FIGURE 13. TOTAL EMISSIONS CHARACTERISTICS FOR A TCM 6-285-B (TIARA) ENGINE OPERATING UNDER VARYING SEA LEVEL INDUCTION AIR TEMPERATURES (TAKEOFF AND CLIMB MODES BOTH SET TO 100-PERCENT POWER)--PRODUCTION RICH LIMIT

NOTE:
1. THIS FIGURE IS BASED ON THE TABLE 4 LTO CYCLE WITH THE CLIMB MODE AT 100 PERCENT POWER.
2. THE MINIMUM F/A RATIO SETTINGS FOR THIS FIGURE ARE 0.0705 FOR THE APPROACH MODE AND 0.075 FOR THE TAXI MODE; TAKEOFF AND CLIMB WERE SET FOR A FUEL FLOW OF 150 lb/h - - THESE SETTINGS APPLY TO THE LOWEST BARGRAPH GROUP

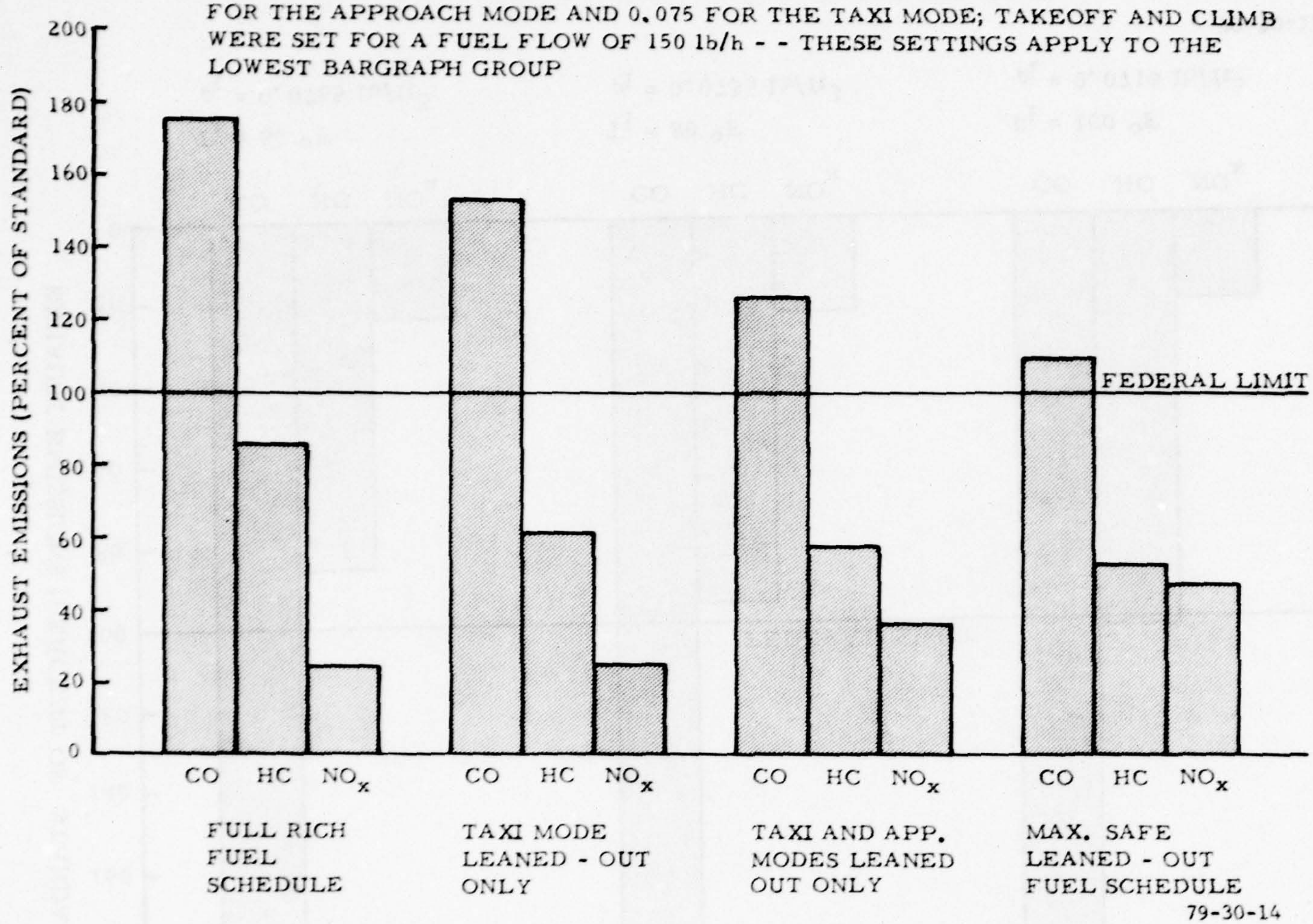

FIGURE 14. TOTAL EMISSIONS CHARACTERISTICS FOR A TCM 6-285-B (TIARA) ENGINE WITH DIFFERENT FUEL SCHEDULE ADJUSTMENTS--SEA LEVEL STANDARD DAY (TAKEOFF AND CLIMB MODES BOTH SET TO 100-PERCENT POWER)

TABLE 6. SUMMARY OF EXHAUST EMISSIONS (CO) REDUCTION POSSIBILITIES FOR A TCM 6-285-B ENGINE—SEA LEVEL STANDARD DAY (EXCEPT AS NOTED)—COOLING AIR P=3.0 inH2O

	Mode Parameter	F/A	CO lb/Mode	Max. CHT-°F	F/A	CO lb/Mode	Max. CHT-°F	Max. CHT-°F	F/A	Cooling Air P-inH2O
1	Taxi	0.0900	5.600	-	0.0750	2.933	-	-	0.0750	0
2	Takeoff (100%)	0.0880	0.588	440	0.0815	0.475	460	485	0.0860	3.0
3	Climb (100%)	0.0880	9.792	440	0.0815	7.917	460	485	0.0860	3.0
4	Approach	0.0785	5.000	365	0.0705	1.800	375	390	0.0735	3.0
5	lb/Cycle		20.980			13.125				
6	lb/Cycle/RBHP		0.0736			0.0461				
7	Federal Limit		0.042			0.042				
8	Diff. = 6 - 7		0.0316			0.0041				
9	(8 ÷ 7) x 100		75.2			9.8				
10	% of STD = 9 + 100		175.2			109.8				
				This Column For SL. Standard Day			This Column For SL. Standard Day	This Column For SL. Hot Day	This Column For SL. Hot Day	
11	Taxi	0.0900	5.600	-	0.0750	2.933	-	-	0.0750	0
12	Takeoff (100%)	0.0880	0.588	440	0.0815	0.475	460	485	0.0860	3.0
13	Climb (80%)	0.0820	7.208	425	0.0750	4.000	430	445	0.0795	3.0
14	Approach	0.0785	5.000	365	0.0705	1.800	375	390	0.0735	3.0
15	lb/Cycle		18.396			9.208				
16	lb/Cycle/RBHP		0.065			0.0323				
17	Federal Limit		0.042			0.042				
18	Diff. = 16 - 17		0.023			-.0097				
19	(18 ÷ 17) x 100		53.7			-23.1				
20	% of STD = 19 + 100		153.7			76.9				

1. Ambient conditions (pressure, temperature, and density)--SL. standard day
2. Fuel schedule--production rich setting
3. Power setting--100%
4. Measured max. CHT--440° F
5. Max. CHT limit--460° F
6. Margin-- 5 minus 4 — 20° F

If we now adjust this engine fuel schedule setting to best power or max. CHT limit (all other parameters constant based on above conditions), we now find the following changes take place:

1. CO emissions are improved approx. 65.5% (nominal)
2. Measured max. CHT increases 4.5% (from 440° F to 460° F)
3. Max. CHT limit--460° F
4. Margin-- 3 minus 2 = 0° F
5. Reduction in margin (max CHT)—(20÷20) x 100 = 100.0%

Now, if we apply the above results to a SL. hot-day condition, we arrive at the following results:

Production Rich Limit Schedule (maximum available power)

1. Ambient conditions--SL. hot day (100° F)
2. Fuel schedule--production rich setting
3. Power setting--maximum available based on CHT limit (95-100% EST.)
4. Measured max. CHT—460° F
5. Max. CHT limit--460° F
6. Margin-- 5 minus 4 = 0° F

Best Power Fuel Schedule (maximum available power)

1. Ambient conditions--SL. hot day
2. Fuel schedule--best power fuel schedule
3. Power setting--85-90% (EST.)
4. Measured max. CHT--460°F
5. Max. CHT limit--460°F
6. Margin--5 minus 4 = 0°F

NOTE: This hot-day example indicates that the engine operating at constant ΔP cooling air conditions must be operated at reduced power when taking off and climbing under leaned-out fuel schedule settings.

EFFECTS OF LEANING-OUT ON HC EMISSIONS. The test data show that the TCM 6-285-B engine meets the federal standard for unburned hydrocarbon emissions when operating at the production rich limit fuel flows (figures 11, 12, 13, and 14). Additional leaning-out in the taxi, approach, and climb modes provides added improvements, but is not required to produce HC emission levels below the federal standard.

EFFECTS OF LEANING-OUT ON NO_x EMISSIONS. Oxides of nitrogen emissions are not improved as a result of applying lean-out adjustments to the fuel metering devices. In fact, the NO_x levels are at their lowest when the engine is operating full rich as shown in figures 11, 12, 13, and 14.

EFFECTS ON ALLOWABLE MAXIMUM CYLINDER HEAD TEMPERATURE. One of the major problems that occurs as an effect of leaning-out general aviation piston engines in order to improve emissions is the increase or rise in maximum cylinder head temperatures.

Most general aviation aircraft are designed to operate with cooling air pressure differentials of 4.0 inH_2O or less. The tests conducted with the TCM 6-285-B engine utilized 3.0 inH_2O as the basic cooling flow condition, except in the taxi mode where the cooling air ΔP was essentially zero.

No tests were conducted using variations in cooling air flow to evaluate these effects on different lean-out schedules.

Data shown in tables C-1 through C-21 and plotted in figures 15 through 17 show the results of these tests.

In summary it can be concluded that any attempts to lean-out current production-type horizontally opposed general aviation piston engines in the takeoff mode to F/A ratios lower than production lean limits will produce CHT's that are higher than the manufacturer's specified limit.

Any attempt to lean-out the climb mode to F/A ratios below best power will result in higher than normal CHT's. This could become particularly acute under hot-day takeoff and climb conditions at sea level or altitude.

RESULTS OF TESTS WITH VARYING SPARK SETTINGS.

This engine was evaluated with different spark settings. The basic production setting is 30° before top dead center (BTC). Two other settings were evaluated 45° BTC and 21° BTC. Table 7 summarizes the results of all the tests conducted and presents the data on an average basis. The three basic power modes (takeoff, climb, and approach--100, 75-80, and 40 percent, respectively) are tabulated using average data based on three test runs for each power mode condition and each spark setting.

The results of these tests and the percent changes in emissions output are also shown in table 7. For a change in the spark setting from 30° BTC to 45° BTC it may be noted that the Δ%CO increases approximately 0.3 to 0.5 in the takeoff and climb modes with a negigible decrease in the approach mode. These changes occur for a 5.0 to 7.7 percent decrease in power, while the takeoff and climb CHT increases from 5.8 to 8.0 percent, respectively, and the approach mode CHT decreases approximately 1.2 percent. Although the percent changes in unburned HC and NO_x appear to be significant, it should be noted that both of these pollutants are measured on a fraction of a percent basis.

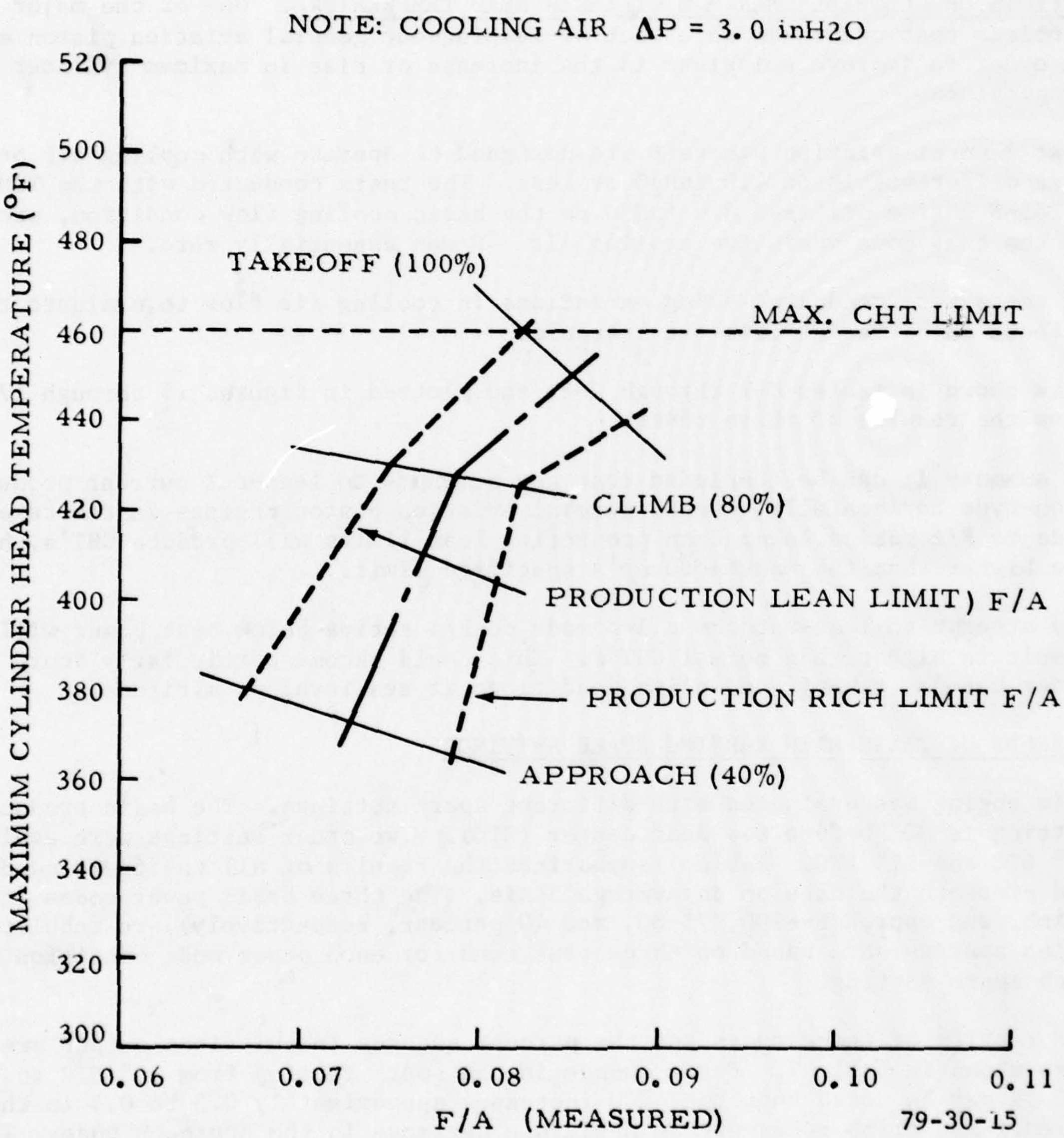

FIGURE 15. SEA LEVEL STANDARD-DAY MAXIMUM CYLINDER HEAD TEMPERATURE FOR DIFFERENT POWER MODE CONDITIONS AND VARYING FUEL-AIR-RATIOS--TCM 6-285-B (TIARA) ENGINE

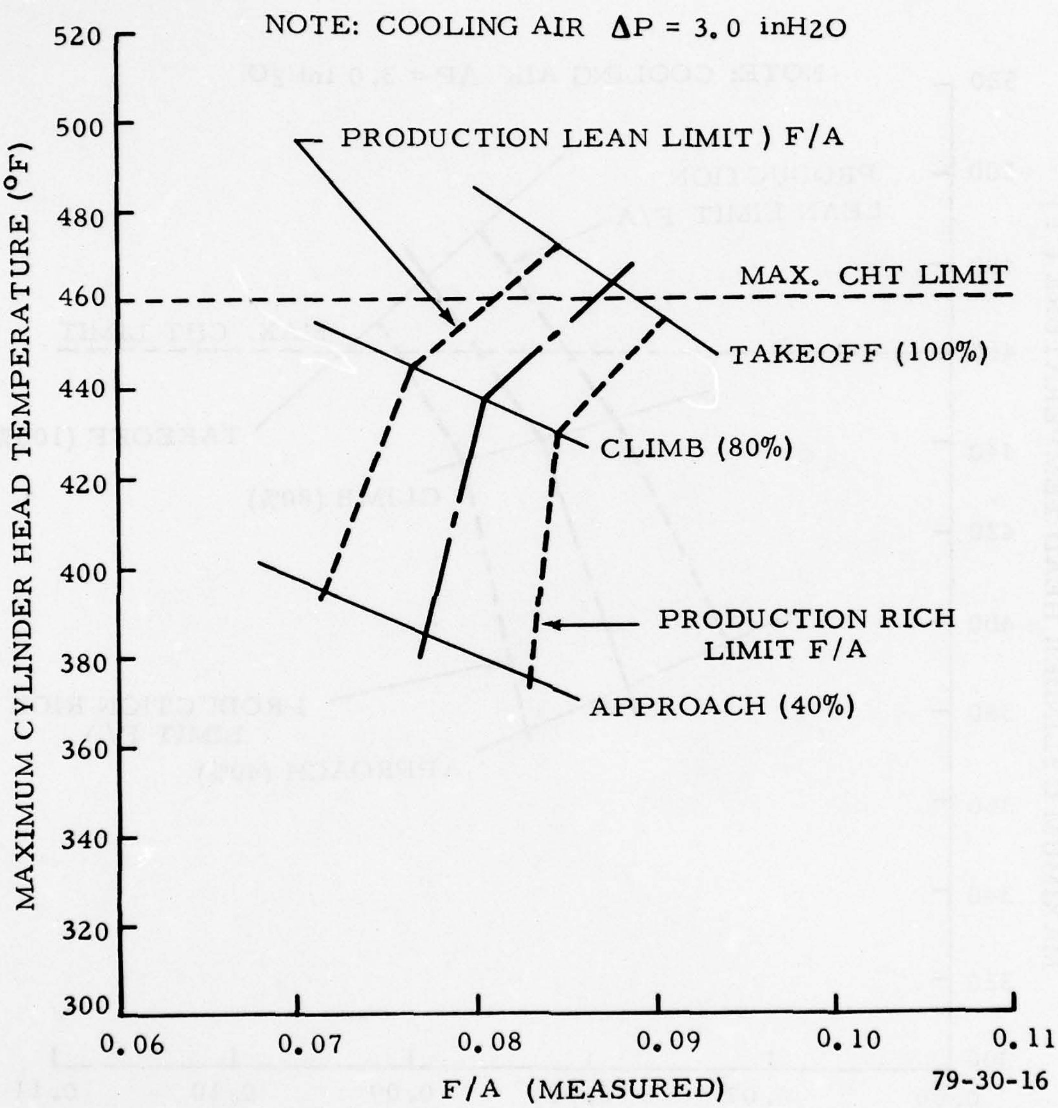

FIGURE 16. SEA LEVEL WARM-DAY (T_i-80° F) MAXIMUM CYLINDER HEAD TEMPERATURE FOR DIFFERENT POWER MODE CONDITIONS AND VARYING FUEL-AIR-RATIOS-- TCM 6-285-B (TIARA) ENGINE

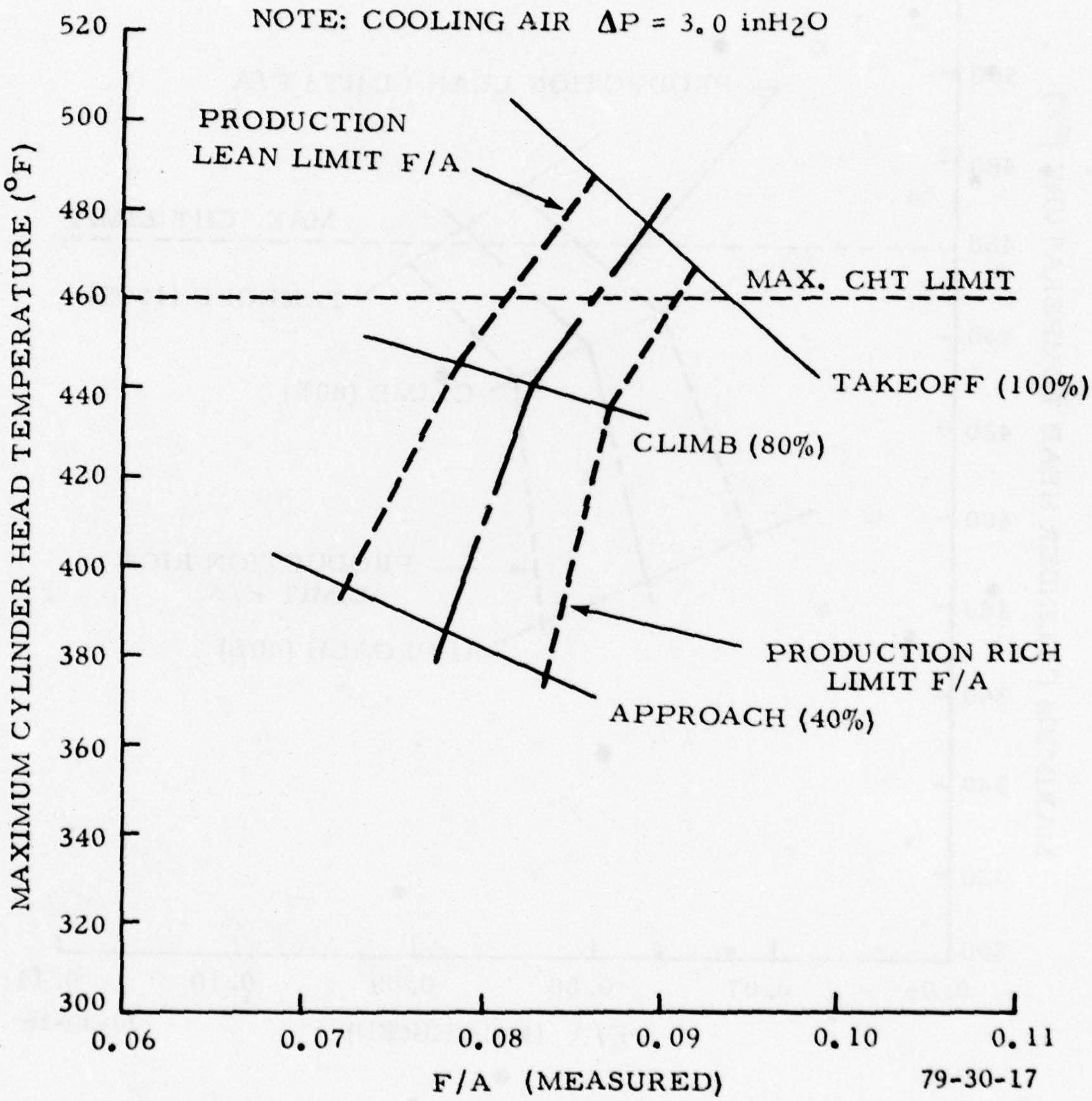

FIGURE 17. SEA LEVEL HOT-DAY (T_i-100° F) MAXIMUM CYLINDER HEAD TEMPERATURE FOR DIFFERENT POWER MODE CONDITIONS AND VARYING FUEL-AIR-RATIOS--TCM 6-285-B (TIARA) ENGINE

TABLE 7. SUMMARY OF ENGINE PERFORMANCE AND EXHAUST EMISSIONS CHARACTERISTICS FOR THREE DIFFERENT SPARK SETTINGS (°BTC)--FULL RICH FUEL SCHEDULE

Mode Cond.	Meas. Torq. lb-ft 30° BTC	Meas. BHP 30° BTC	Avg. Ind. Air Temp. (°F)	Avg. W_f lb/h	Avg. Wa lb/h	F/A	Avg. $\%CO_2$	Avg. %CO	Avg. HC-PPM	Avg. NO_x-PPM	Avg. Max. CHT (°F)	Run No.
Takeoff	640	244	65	173	1813	0.0954	9.30	9.08	1876	235	416	77, 102, 115
Climb	606	208	66	130	1497	0.0868	10.21	7.68	1841	371	401	78, 103, 116
Approach	299	99	66	75	848	0.0884	8.80	10.17	2846	179	345	79, 104, 117
	Meas. Torq. lb-ft 45° BTC	Meas. BHP 45° BTC										
Takeoff	605	230	65	174	1793	0.0970	8.83	9.44	3267	315	440	143, 148, 170
Climb	559	192	65	129	1468	0.0879	9.61	8.22	3021	440	433	144, 152, 171
Approach	285	94	65	73	821	0.0889	8.43	10.11	3763	248	340	145, 156, 172
	Meas. Torq. lb-ft 21° BTC	Meas. BHP 21° BTC										
Takeoff	598	228	65	174	1840	0.0946	9.39	8.50	1934	162	410	177, 182, 944
Climb	559	192	65	130	1518	0.0856	10.10	7.58	1984	232	401	178, 186, 945
Approach	272	90	67	74	851	0.0870	8.86	9.95	3043	113	338	179, 190, 946

		ΔTorq. lb-ft	ΔBHP	Nominal Ind. Air Temp. (°F)	% ΔBHP	$\Delta\%CO_2$	Δ%CO	ΔHC(%)	ΔNO_x(%)	% ΔCHT(Max)
Takeoff	30°-45° BTC	-35	-14	65	-5.74	-0.47	+0.32	+74.15	+34.04	+5.77
Climb	30°-45° BTC	-47	-16	65.5	-7.69	-0.60	+0.54	+64.10	+18.60	+7.89
Approach	30°-45° BTC	-14	- 5	65.5	-5.05	-0.37	-0.06	+32.22	+38.55	-1.15
Takeoff	30°-21° BTC	-27	-16	65	-6.56	+0.09	-0.58	+ 3.09	-31.06	-1.44
Climb	30°-21° BTC	-47	-16	65.5	-7.69	-0.11	-0.01	+ 7.76	-37.47	0
Approach	30°-21° BTC	-27	- 9	66.5	-9.09	+0.06	-0.22	+ 6.61	-36.87	-2.03

Changing the spark setting from 30° BTC to 21° BTC shows that the %CO decreases from 0.2 to 0.6 in the approach and takeoff modes with a negligible decrease in the climb mode. These changes occur for a 6.6 to 9.1 percent decrease in power, while the takeoff and approach mode CHT decreases from 1.4 to 2.0 percent. No change was measured in the climb mode CHT. The percent changes in unburned HC and NO_x appear to be significant. Whereas, the HC and NO_x both increased for a spark setting change from 30° BTC to 45° BTC; the HC increased and the NO_x decreased the a spark setting change from 30° BTC to 21° BTC.

The data presented in table 7 and the plotted results in figures 18 through 20 for the three power conditions and spark settings indicate that the most optium condition for the TCM 6-285-B (TIARA) engine is the 30° BTC spark setting. Any deviation from this setting will not produce the most benefical results (lower power available conditions, higher CHT's with the 45° BTC setting, etc).

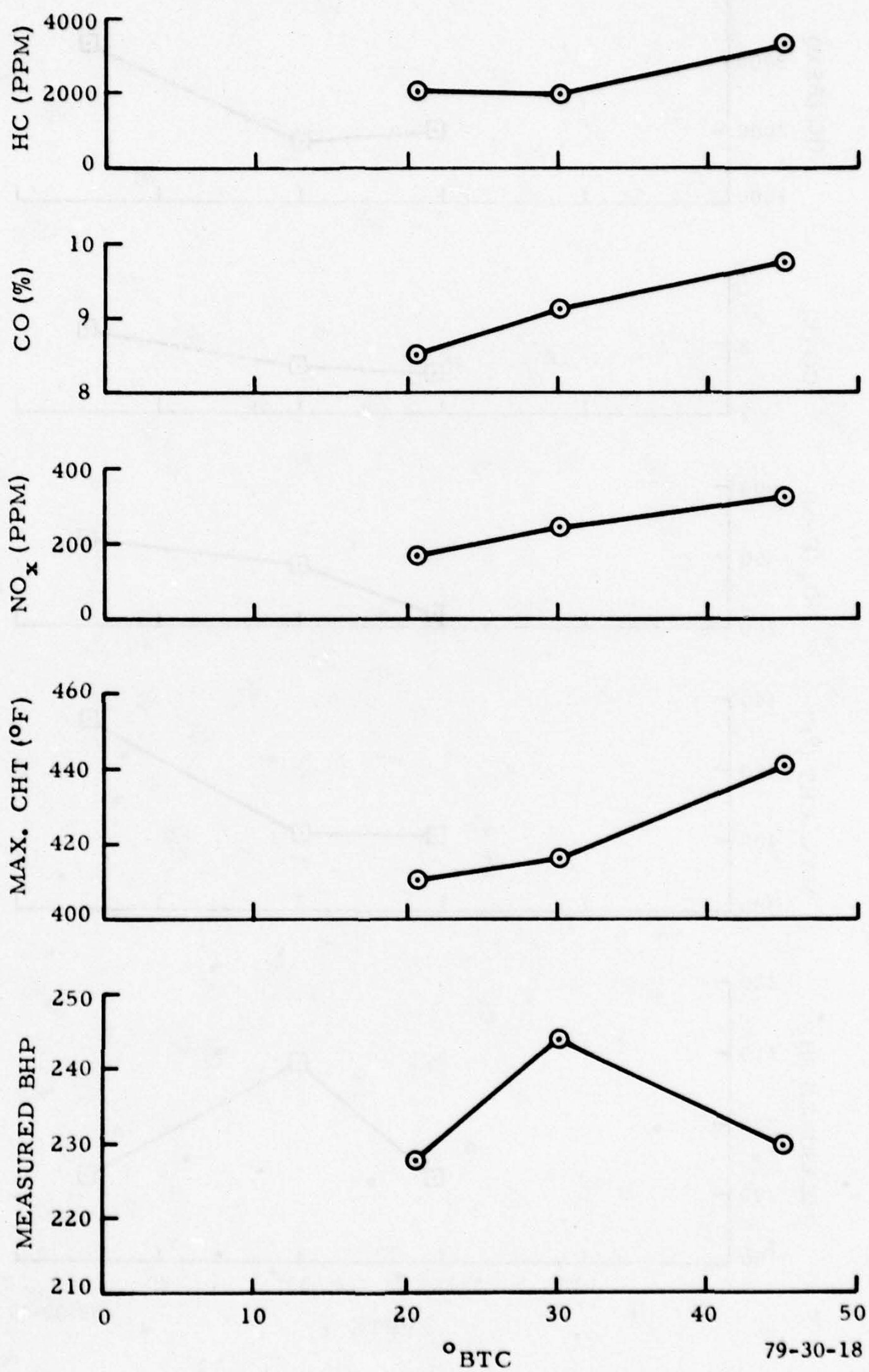

FIGURE 18. EFFECT OF VARYING SPARK SETTING ON ENGINE PERFORMANCE AND EXHAUST EMISSIONS--TAKEOFF MODE

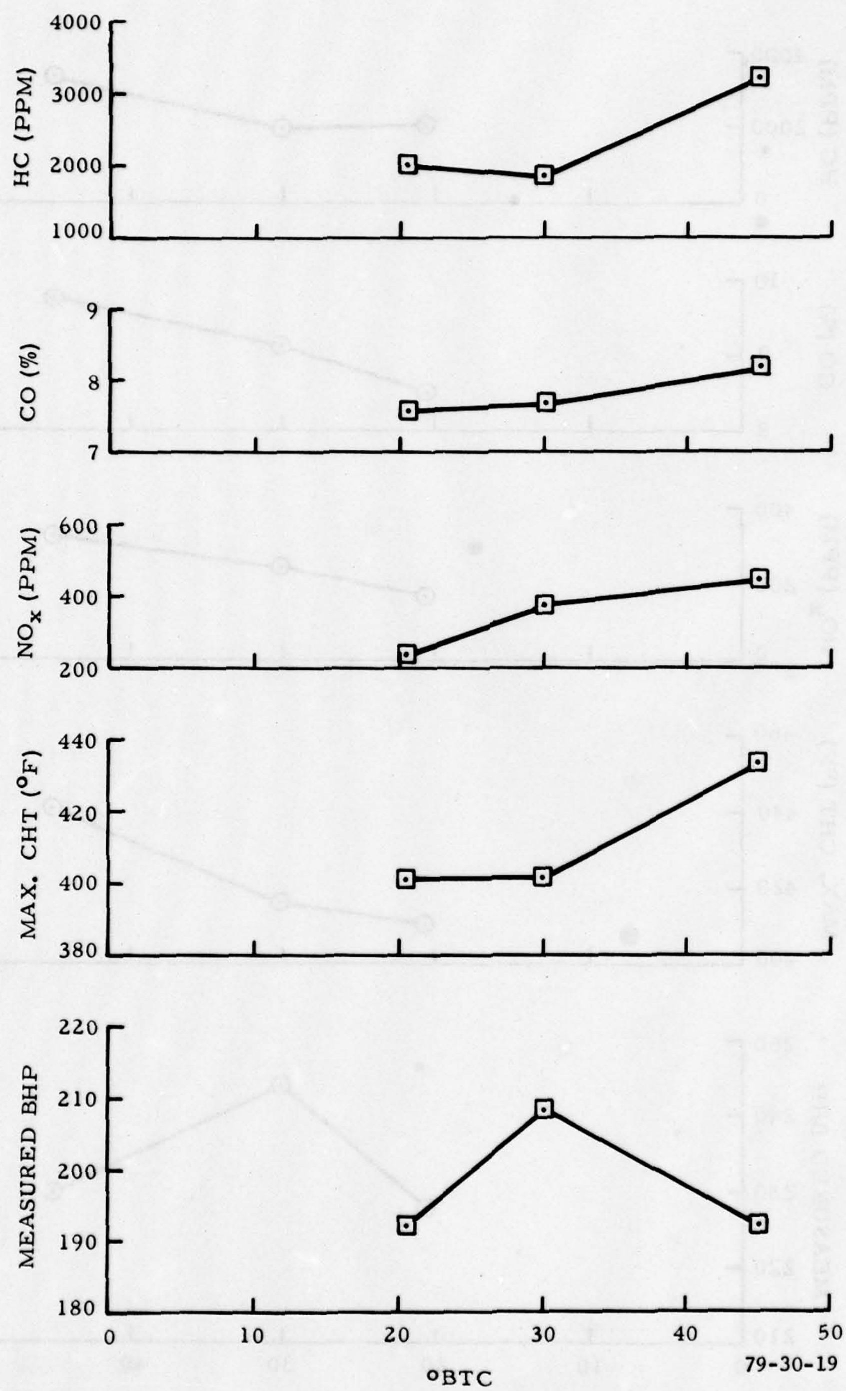

FIGURE 19. EFFECT OF VARYING SPARK SETTING ON ENGINE PERFORMANCE AND EXHAUST EMISSIONS--CLIMB MODE

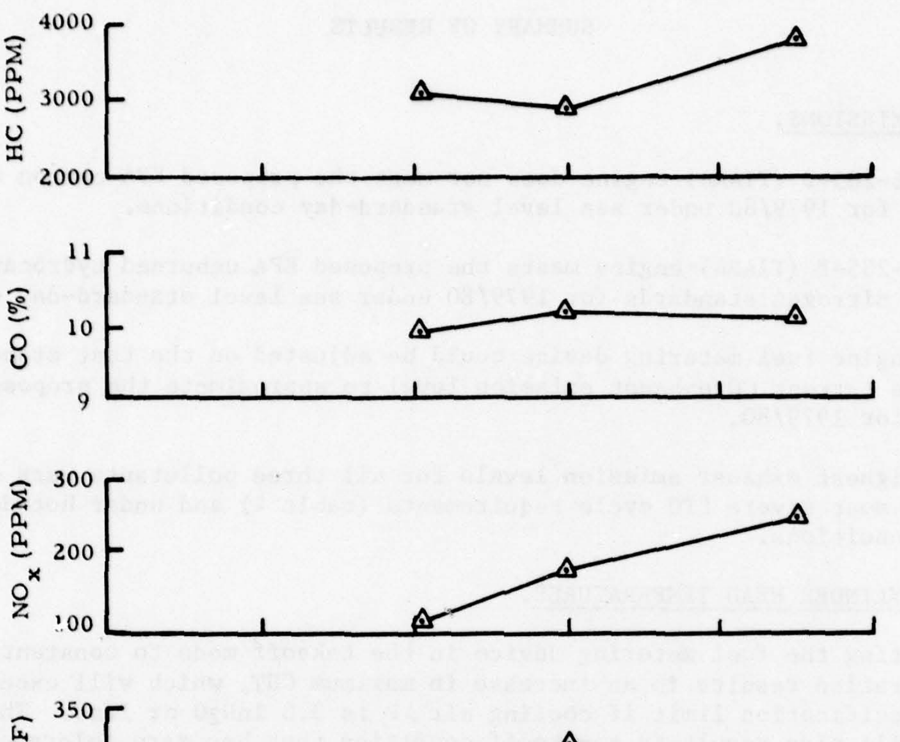

FIGURE 20. EFFECT OF VARYING SPARK SETTING ON ENGINE PERFORMANCE AND EXHAUST EMISSIONS--APPROACH MODE

SUMMARY OF RESULTS

EXHAUST EMISSIONS.

1. The 6-285-B (TIARA) engine does not meet the proposed EPA carbon monoxide standards for 1979/80 under sea level standard-day conditions.

2. The 6-285-B (TIARA) engine meets the proposed EPA unburned hydrocarbon and oxides of nitrogen standards for 1979/80 under sea level standard-day conditions.

3. The engine fuel metering device could be adjusted on the test stand to reduce the current CO exhaust emission level to approximate the proposed EPA standard for 1979/80.

4. The highest exhaust emission levels for all three pollutants were measured under the most severe LTO cycle requirements (table 4) and under hot-day, ambient conditions.

MAXIMUM CYLINDER HEAD TEMPERATURES.

1. Adjusting the fuel metering device in the takeoff mode to constant best power operation results in an increase in maximum CHT, which will exceed the engine specification limit if cooling air ΔP is 3.0 inH_2O or less. This setting will also result in a takeoff condition that has zero tolerance/margin.

2. Adjusting the fuel metering device in the climb mode to constant best power will result in an increase in maximum CHT. This change would necessitate an increase in cooling air flow to provide adequate temperature margins for hot-day operations. An increase in cooling air differential pressure of approximately 1.0 inH_2O may be required for critical aircraft installations.

3. No critical maximum CHT's resulted from leaning-out the approach and taxi modes. However, taxi mode maximum CHT's were measured in excess of 400° F while operating under leaned-out test conditions with no measurable cooling air ΔP, a condition related to actual operation.

CRITICAL LANDING AND TAKEOFF CYCLE.

1. The most critical LTO cycle is the cycle defined in this report as the maximum five-mode LTO cycle (table 4). Engine operation in accordance with the maximum five-mode LTO cycle in a sea level propeller test stand could be adjusted to approximate the proposed EPA CO emission standard for 1979/80 without exceeding maximum CHT limits.

2. Engine operation in accordance with the minimum five-mode LTO cycle (table 5) could be adjusted to meet the proposed EPA emissions standards for 1979/80 without exceeding engine maximum CHT limits while operating with a cooling air $\Delta P = 3.0$ inH_2O in the takeoff, climb, and approach modes and a $\Delta P = 0$ in the taxi mode.

OPTIMUM SPARK SETTING.

1. The 30° BTC spark setting produces optimum test results:

a. Optimum power
b. Optimum CHT
c. Emissions that are most compatible with desired power output and CHT limits.

CONCLUSIONS

The following conclusions are based on the testing accomplished with the TCM 6-285-B (TIARA) engine.

1. The single use of simple fuel management adjustments (altering of fuel schedule) does not allow safe reduction of exhaust emissions of the test engine, the TCM 6-285-B. In conjuction with other data, references 12, 13, and 14, this appears to be a valid general conclusion for typical light-aircraft piston engines.

2. The test data indicate that fuel management adjustments should be combined with engine/nacelle cooling modifications before a safe, low-emissions aircraft/engine combination can be achieved.

3. Spark settings other than the 30° BTC setting do not appear to produce significantly beneficial improvements in exhaust emissions.

4. The EPA CO limit of 0.042 lb/cycle/rated BHP is too low to be met by this engine. This limit appears to be only approximately achievable when hot-day takeoff and climb requirements are impacted by aircraft heavy gross weight and the need to pay close attention to CHT limitations. The TIARA engine is particularly critical under these operational requirements since it is a powerplant designed tor agricultural-type aircraft which require high power performance under heavy gross weight and warm-/hot-day ambient conditions.

5. Based on an assessment of the maximum five-mode LTO cycle (table 4) test data, it is concluded that the following standard changes should be made to the proposed EPA emission standards:

Proposed EPA Standard for 1979/80 (Reference 1) lb/Cycle/Rated BHP	Proposed Change to the 1979/80 Standard lb/Cycle/Rated BHP
CO Standard 0.042	0.075
HC Standard 0.0019	0.0025
NO_x Standard 0.0015	0.0015

6. To avoid CHT problems in the takeoff mode (100 percent power), it is adviseable not to adjust the fuel metering device. Engine operation in this mode should continue to be accomplished within current production rich/lean limits. No change in current maximum CHT limitations will then be required.

7. The test procedures (baseline and lean-out tests) and test techniques used to evaluate the exhaust emissions characteristics of this engine appeared to be satisfactory for sea level propeller stand test work.

8. The instrumentation defined in this report proved to be satisfactory throughout the conduct of tests performed with this engine.

REFERENCES

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14. Becker, E. E., Exhaust Emissions Characteristics for a General Aviation Light-Aircraft TCM TSIO-360-C Piston Engine, DOT/FAA/NAFEC, Report No. FAA-RD-79-14, June 1979.

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APPENDIX A

FUEL SAMPLE ANALYSIS

COMBUSTIBLE ELEMENTS IN FUELS (AVIATION FUEL).

1. Carbon and hydrogen are the predominant combustible elements in fuels (aviation type), with small amounts of sulphur as the only other fuel element.

2. Liquid fuels are mixtures of complex hydrocarbons.

3. For combustion calculations, gasoline or fuel oil can be assumed to have the average molecular formula C_8H_{17}.

Note: The Exxon data presented in table A-1 may be found in reference 7.

TABLE A-1. TYPICAL SPECIFICATIONS FOR AVIATION FUELS

Item	D910-76 Grade 100/130	Exxon Aviation Gas 100/130	D910-70 Grade 115/145	Exxon Aviation Gas 115/145
Freezing Point, °F	-72 Max.	Below -76	-76 Max.	Below -76
Reid Vapor Press., PSI	7.0 Max.	6.8	7.0 Max.	6.8
Sulfur, % by Weight	0.05 Max.	0.02	0.05 Max.	0.02
Lower Heating Value, BTU/lb	18,720 Min.		18,800 Min.	
Heat of Comb. (NET). BTU/lb		18,960		19,050
Distillation, %Evaporated				
At 167° F (Max.)	10	22	10	21
At 167° F (Min.)	40		40	
At 221° F (Max.)	50	76	50	62
At 275° F (Max.)	90	97	90	96
Distillation End Point	338° F Max.		338° F Max.	
Final Boiling Point °F		319		322
Tel Content, ML/U.S. Gal.	4.0 Max.	3.9	4.6 Max.	4.5
Color	Green	Green	Purple	Purple

4. NAFEC used 100/130 (octane rated) aviation gasoline for the piston engine emission tests. The following analysis of a typical fuel sample (table A-2) made at the U.S. Naval Air Propulsion Test Center (NAPTC), Trenton, N.J. (reference 8).

TABLE A-2. ANALYSIS OF NAFEC FUEL SAMPLE, 100/130 FUEL

Item	NAFEC Sample 100/130	Grade 100/130(MIL-G-5572E) Spec Limits Min.		Max.
Freezing Point, °F	Below -76° F			-76
Reid Vapor Press., PSI	6.12	5.5		7.0
Sulfur % By Weight	0.024			0.05
Lower Heating Value BTU/lb		18,700		
Heat of Comb. (NET) BTU/lb	18,900			
Distillation, % Evaporated			Distillation % Evaporation	
At 158° F	10			
At 167° F (Min.)		167° F	10	
At 167° F (Max.)			40	167° F
At 210° F	40			
At 220° F	50			
At 221° F		221° F	50	
At 242° F	90			
At 275° F		275° F	90	
Distillation End Point	313° F			338° F
Specific Gravity @60° F	0.7071	Report		Report
API Gravity @60° F	68.6		No Limit	
Tel Content, ML/U.S. Gal.	1.84			4.60

Computation for the fuel hydrogen-carbon ratio is based on the fuel net heating value, h_f, equal to 18,900 BTU/lb and figure A-1.

$C/H = 5.6$
$C = 12.011$
$C_8 = 8 \times 12.011 = 96.088$
$H_y = (96.088) \div 5.6 = 17.159$
$H = 1.008$
$Y = (17.159) \div 1.008 = 17.022$ Use $Y = 17$

APPENDIX B

COMPOSITION OF AIR (GENERAL PROPERTIES)

1. Dry air is a mixture of gases that has a representative volumetric analysis in percentages as follows:

Oxygen (O_2)--20.99%
Nitrogen (N_2)--78.03%
Argon (A)--0.94% (Also includes traces of the rare gases neon, helium, and krypton)
Carbon Dioxide (CO_2)--0.03%
Hydrogen (H_2)--0.01%

2. For most calculations it is sufficiently accurate to consider dry air as consisting of:

O_2 = 21.0%
N_2 = 79.0% (including all other inert gases)

3. The moisture or humidity in atmospheric air varies over wide limits, depending on meteorological conditions, its presence in most cases simply implies an additional amount of essentially inert material.

Note: Information given in items 1, 2, and 3 is recommended for computation purposes (reference 3, 4, 9, and 10).

TABLE B-1. MASS ANALYSIS OF PURE DRY AIR

Gas	Volumetric Analysis %	Mole Fraction	Molecular Weight	Relative Weight
O_2	20.99	0.2099	32.00	6.717
N_2	78.03	0.7803	28.016	21.861
A	0.94	0.0094	39.944	0.376
CO_2	0.03	0.0003	44.003	0.013
Inert Gases	0.01	0.0001	48.0	0.002
	100.00	1.000		28.969 = M for air

4. The molecular weight of the apparent nitrogen can be similarly determined by dividing the total mass of the inert gases by the total number of moles of these components:

$$M_{\substack{\text{Apparent}\\\text{Nitrogen}}} = \frac{2225}{79.01} = 28.161$$

5. This appendix advocates the term nitrogen as referring to the entire group of inert gases in the atmosphere and therefore the molecular weight of 28.161 will be the correct value (rather than the value 28.016 for pure nitrogen).

6. In combustion processes the active constituent is oxygen (O_2), and the apparent nitrogen can be considered to be inert. Then for every mole of oxygen supplied, 3.764 moles of apparent nitrogen accompany or dilute the oxygen in the reaction:

$$\frac{79.01}{20.99} = 3.764 \frac{\text{Moles Apparent Nitrogen}}{\text{Mole Oxygen}}$$

7. The information given in items 4, 5, and 6 is recommended for computational purposes in reference 4. Therefore, one mole of air (dry), which is composed of one mole of oxygen (O_2) and 3.764 moles of nitrogen (N_2), has a total weight of 137.998 pounds.

$$(O_2 + 3.764\ N_2) = 137.998$$

This gives the molecular weight of air = 28.97.

APPENDIX C

NAFEC TEST DATA AND WORKING PLOTS FOR ANALYSIS AND EVALUATION, TCM 6-285-B ENGINE

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATION (Continued)

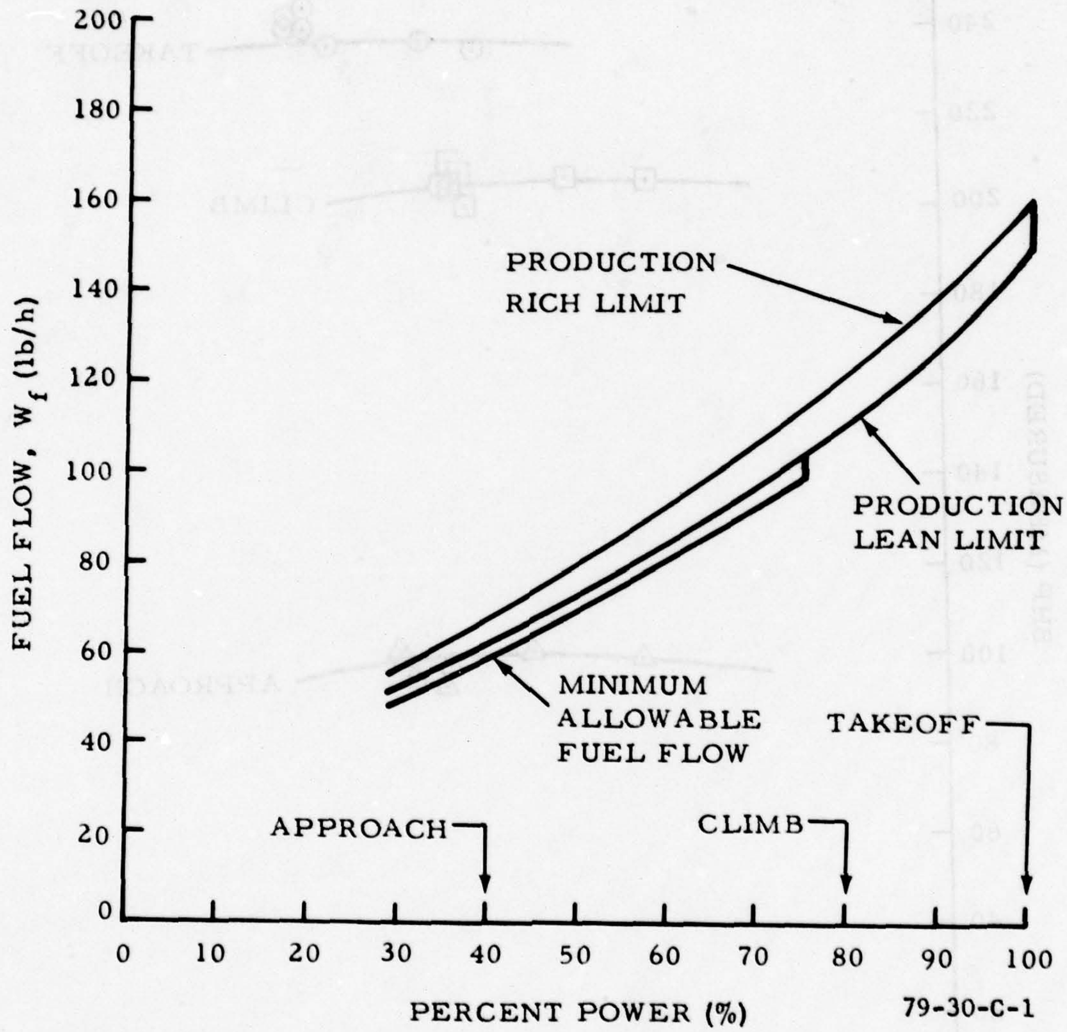


FIGURE C-1. RECOMMENDED FUEL FLOW VERSUS POWER FOR A TCM 6-285-B (TIARA) ENGINE (DERIVED FROM REFERENCE 14)

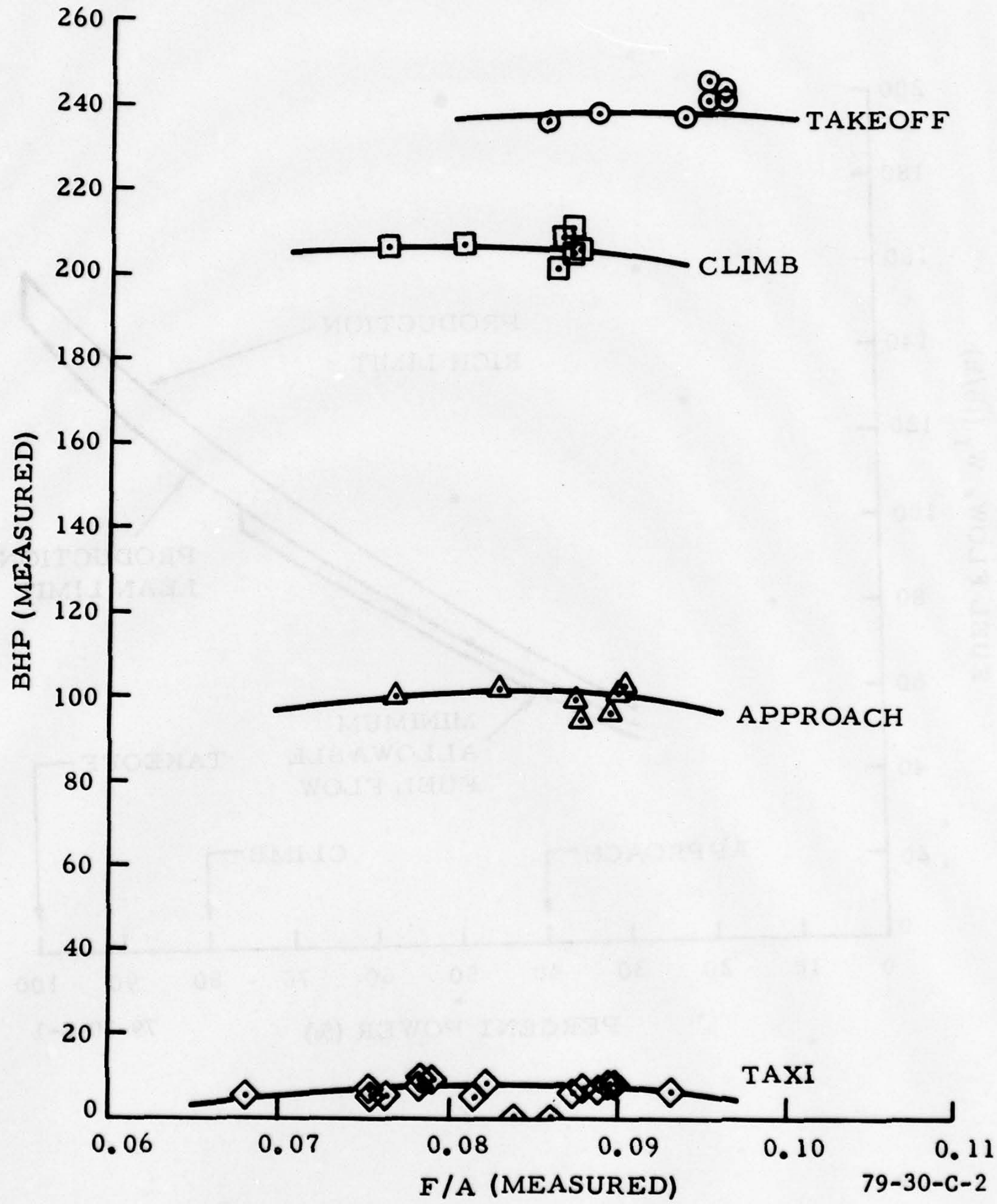


FIGURE C-2. MEASURED PERFORMANCE--TCM 6-285-B (TIARA) ENGINE--TAKEOFF, CLIMB, AND APPRAOCH MODES--NOMINAL SEA LEVEL AIR DENSITY 0.0756 lb.ft^3

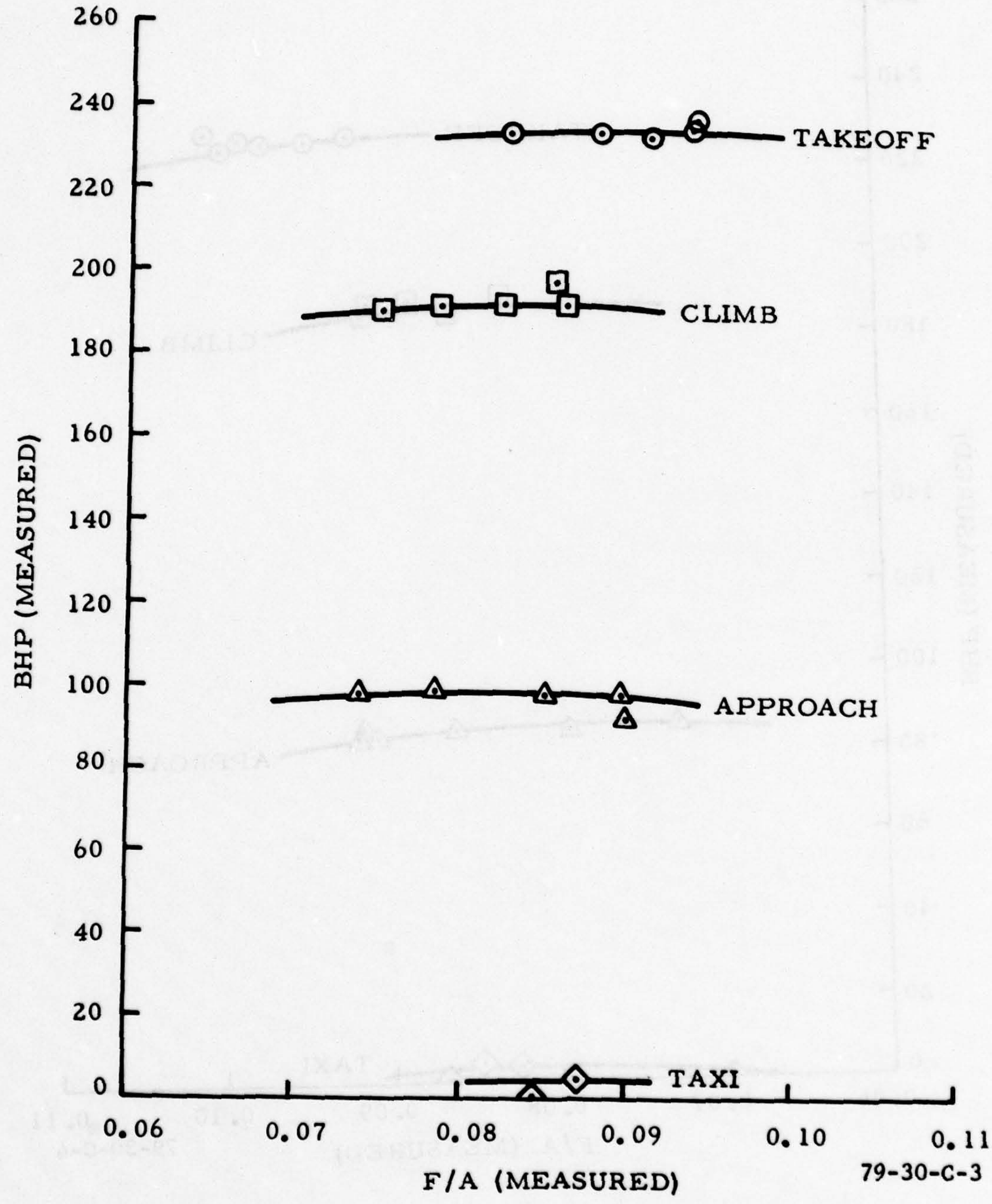


FIGURE C-3. MEASURED PERFORMANCE--TCM 6-285-B (TIARA) ENGINE--TAKEOFF, CLIMB, AND APPROACH MODES--NOMINAL SEA LEVEL AIR DENSITY 0.0730 lb/ft^3

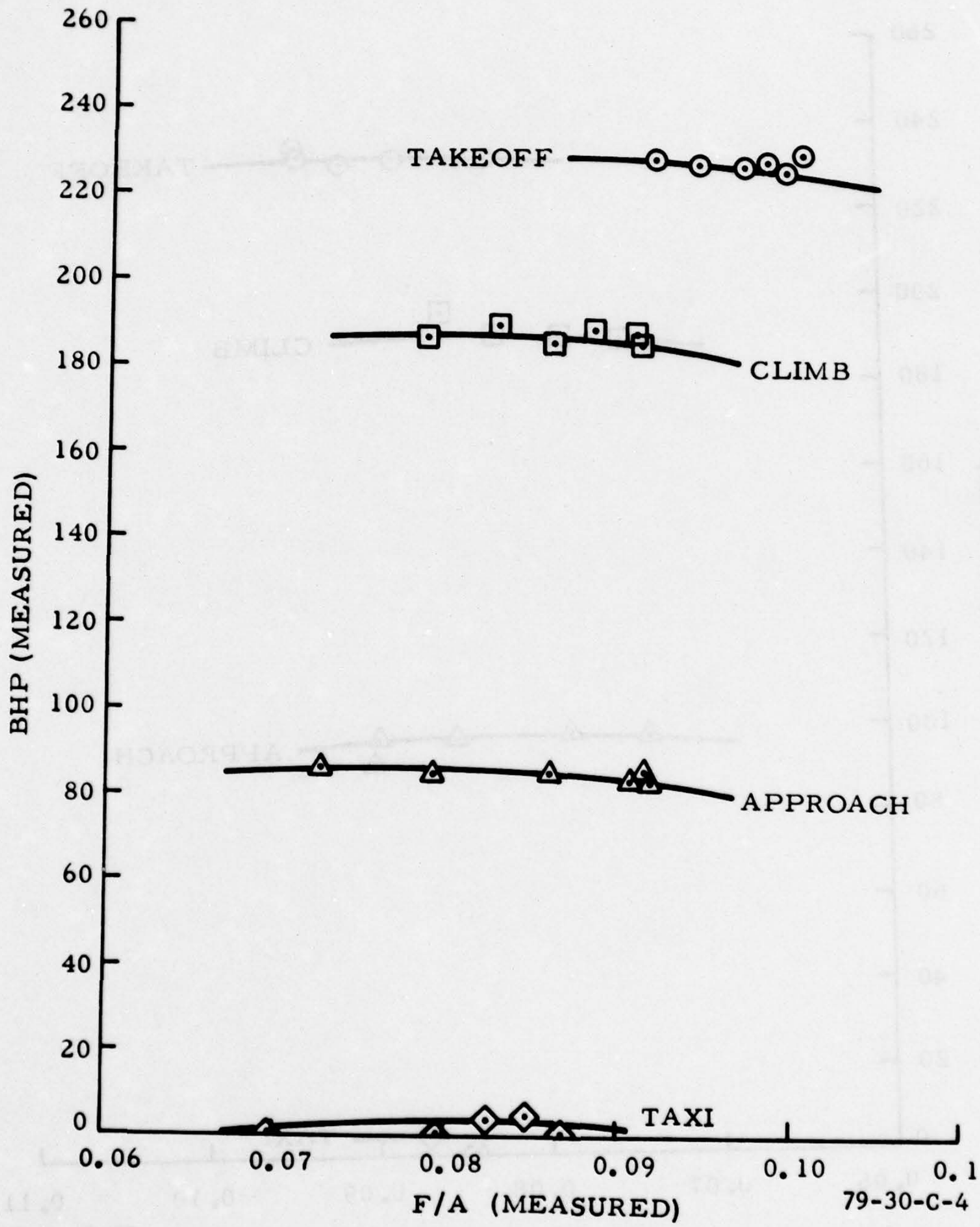


FIGURE C-4. MEASURED PERFORMANCE--TCM 6-285-B (TIARA) ENGINE--TAKEOFF, CLIMB, AND APPROACH MODES--NOMINAL SEA LEVEL AIR DENSITY 0.0684 lb/ft^3

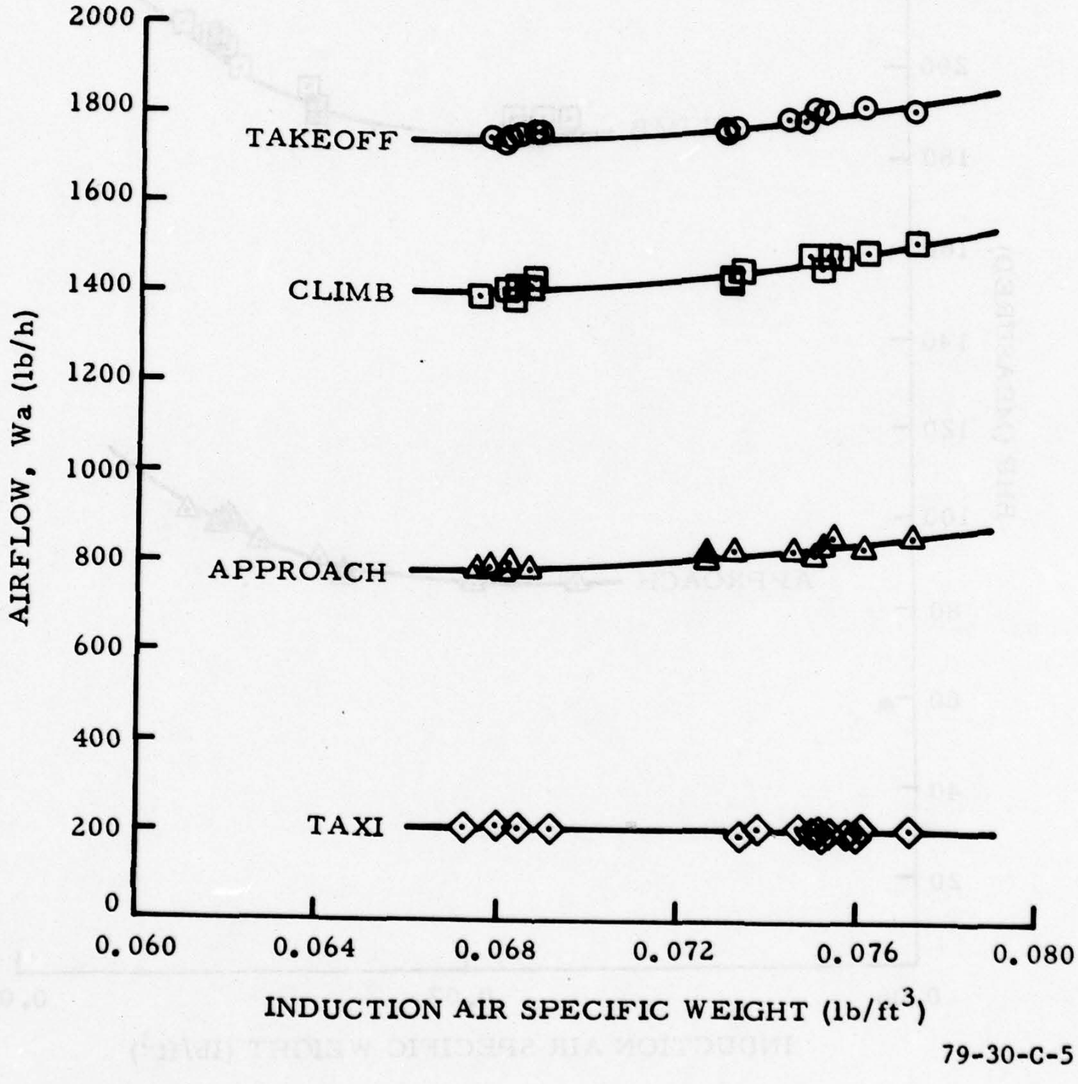


FIGURE C-5. AIRFLOW AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR A TCM 6-285-B (TIARA) ENGINE--NOMINAL SEA LEVEL TEST DATA

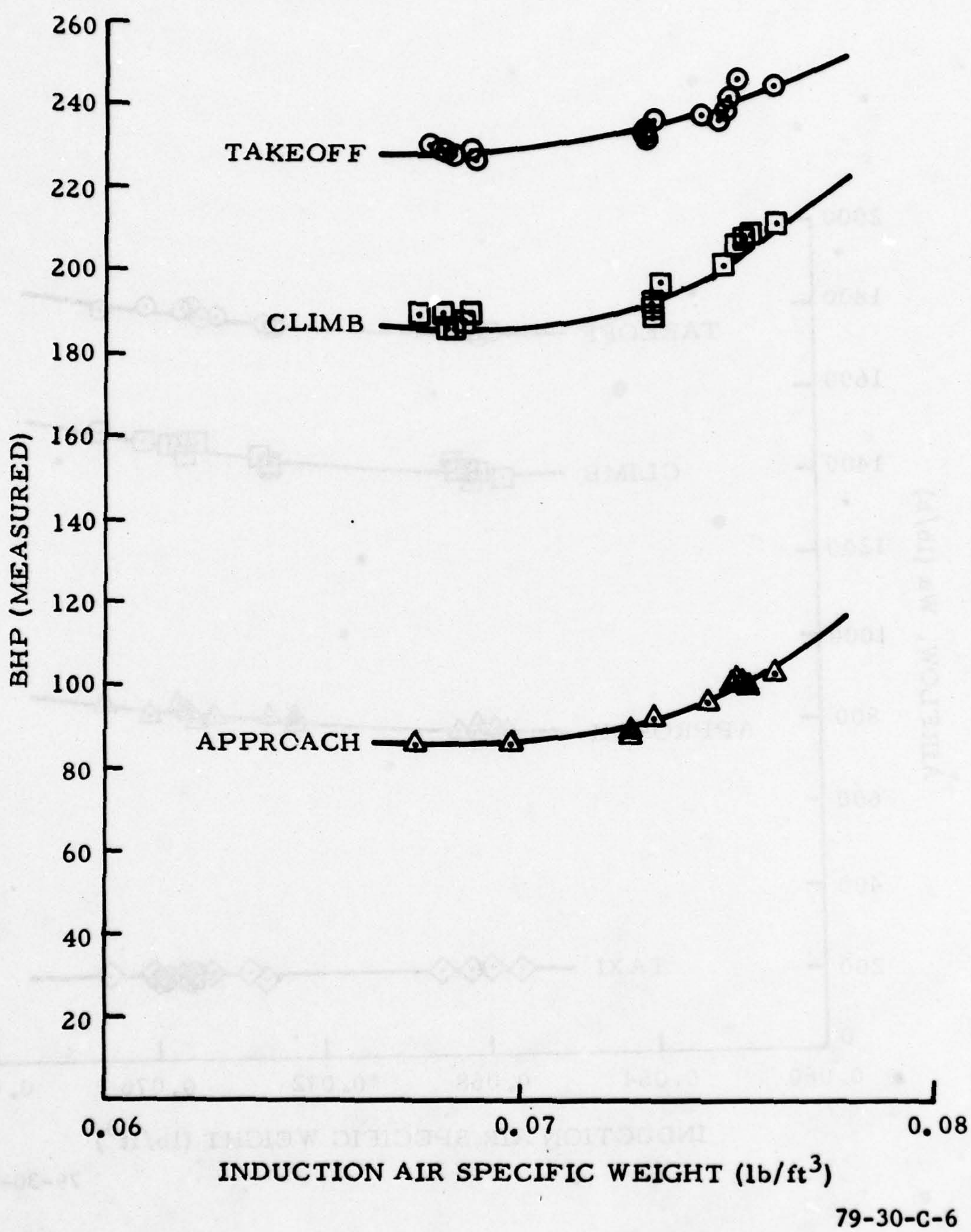


FIGURE C-6. MEASURED BRAKE HORSEPOWER (BHP) AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR A TCM 6-285-B (TIARA) ENGINE--NOMINAL SEA LEVEL TEST DATA

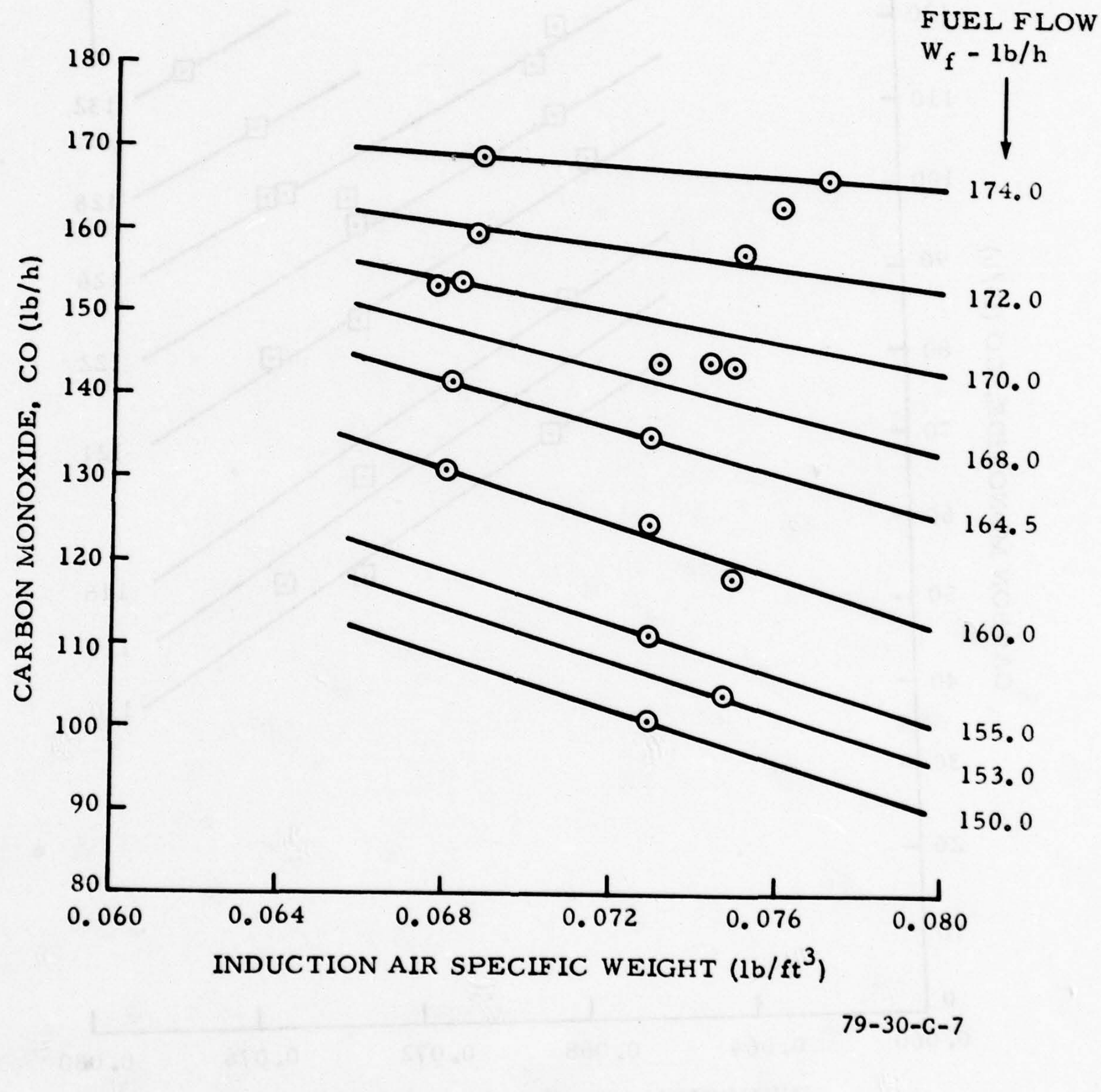
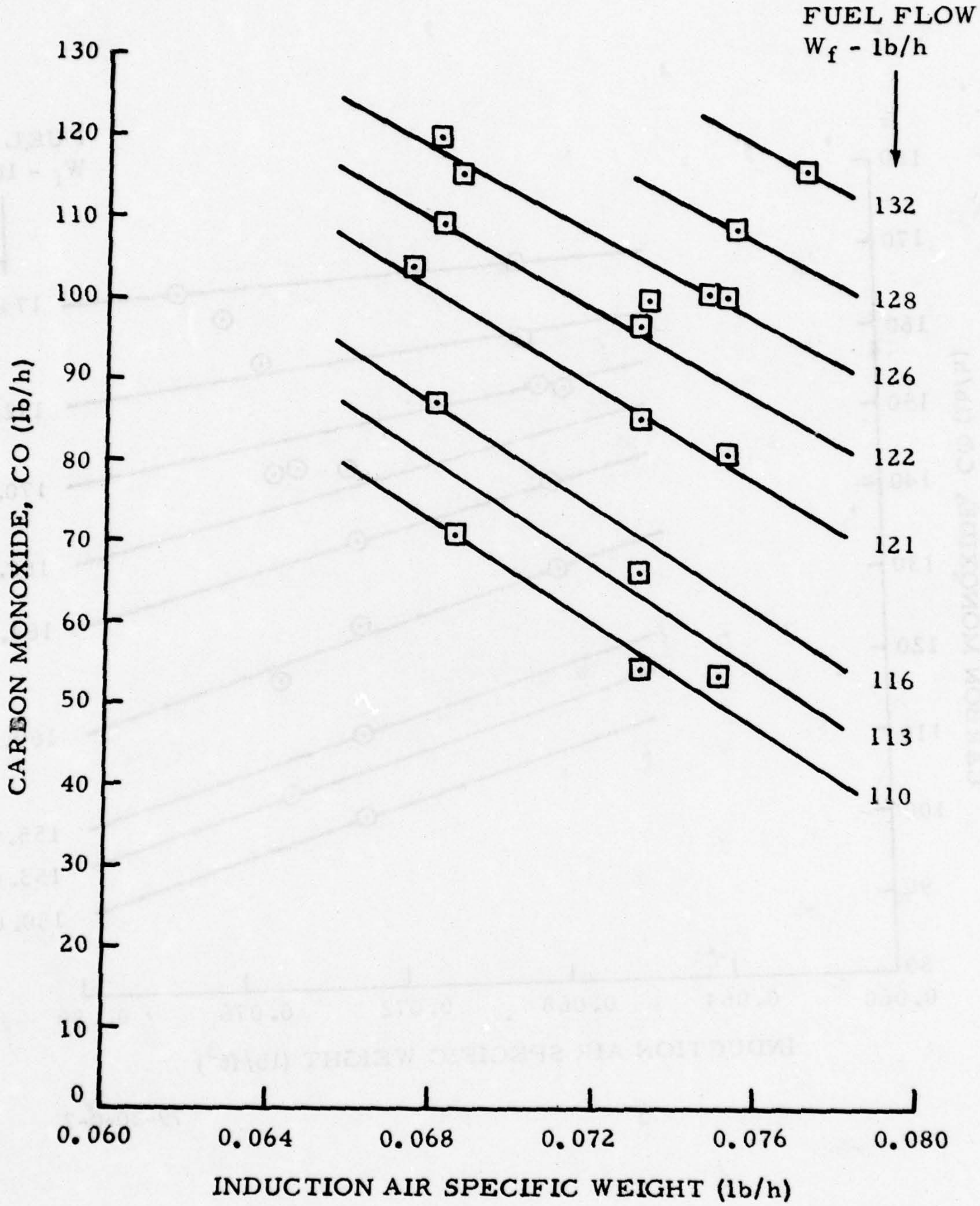


FIGURE C-7. EXHAUST CARBON MONOXIDE AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL TAKEOFF CONSTANT FUEL FLOW SCHEDULES--TCM 6-285-B (TIARA) ENGINE



79-30-C-8

FIGURE C-8. EXHAUST CARBON MONOXIDE AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL CLIMB MODE CONSTANT FUEL FLOW SCHEDULES-- TCM 6-285-B (TIARA) ENGINE

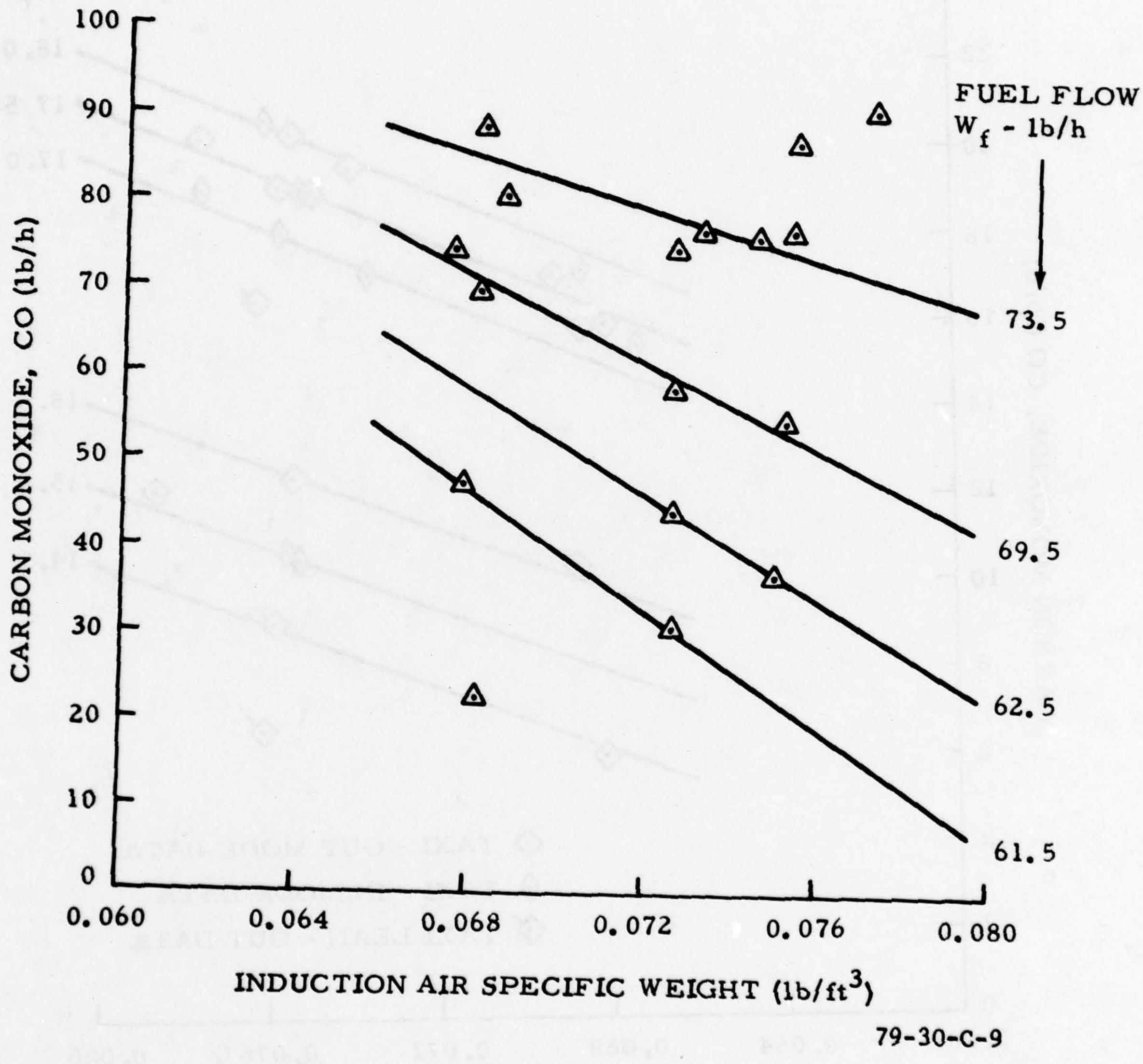


FIGURE C-9. EXHAUST CARBON MONOXIDE AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL APPROACH MODE CONSTANT FUEL FLOW SCHEDULES--TCM 6-285-B (TIARA)

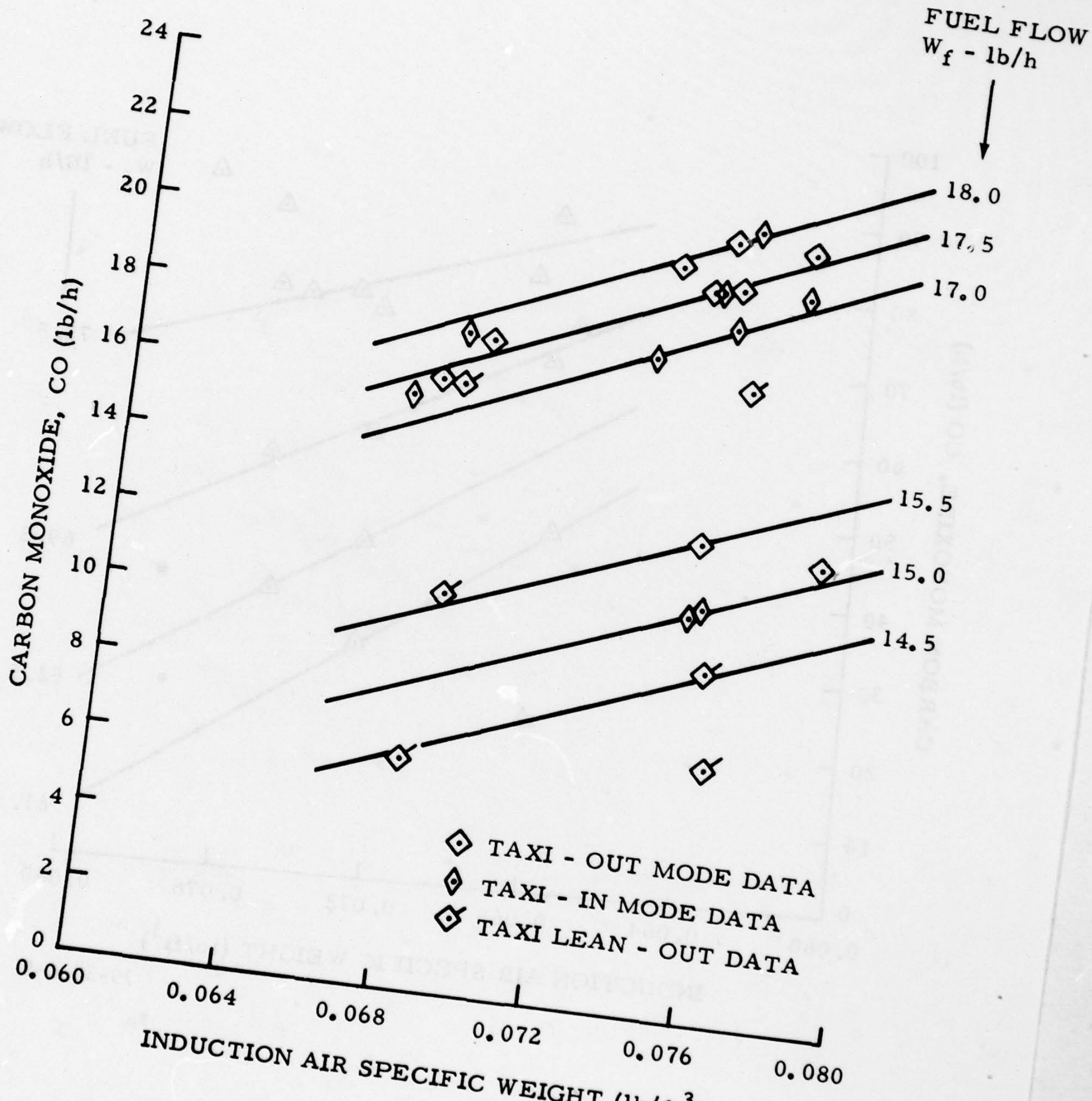


FIGURE C-10. EXHAUST CARBON MONOXIDE AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL TAXI MODE FUEL FLOW SCHEDULES--TCM 6-285-B (TIARA) ENGINE

79-30-C-10

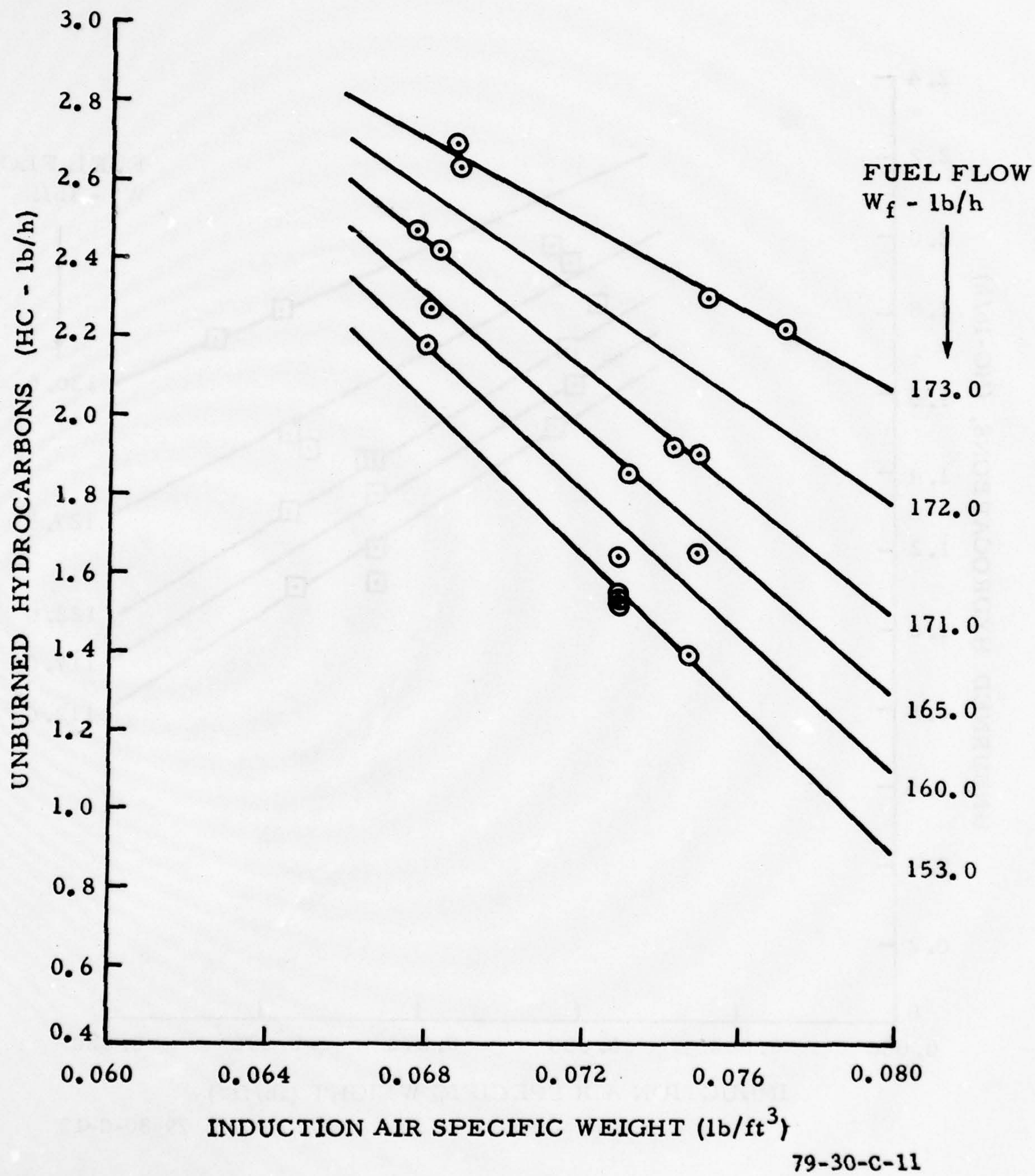


FIGURE C-11. UNBURNED EXHAUST HYDROCARBONS AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL TAKEOFF CONSTANT FUEL FLOW SCHEDULES--TCM 6-285-B (TIARA) ENGINE

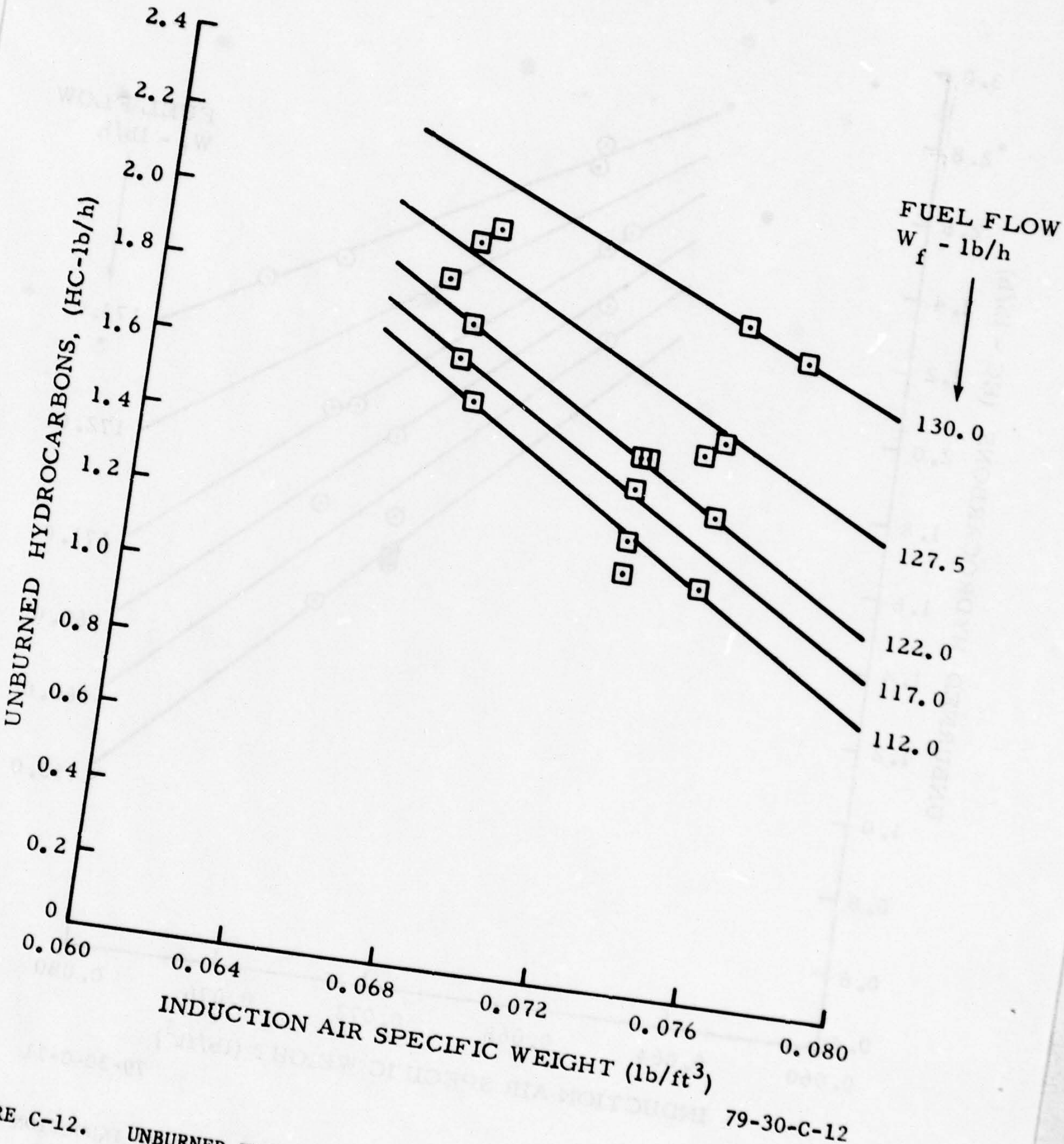
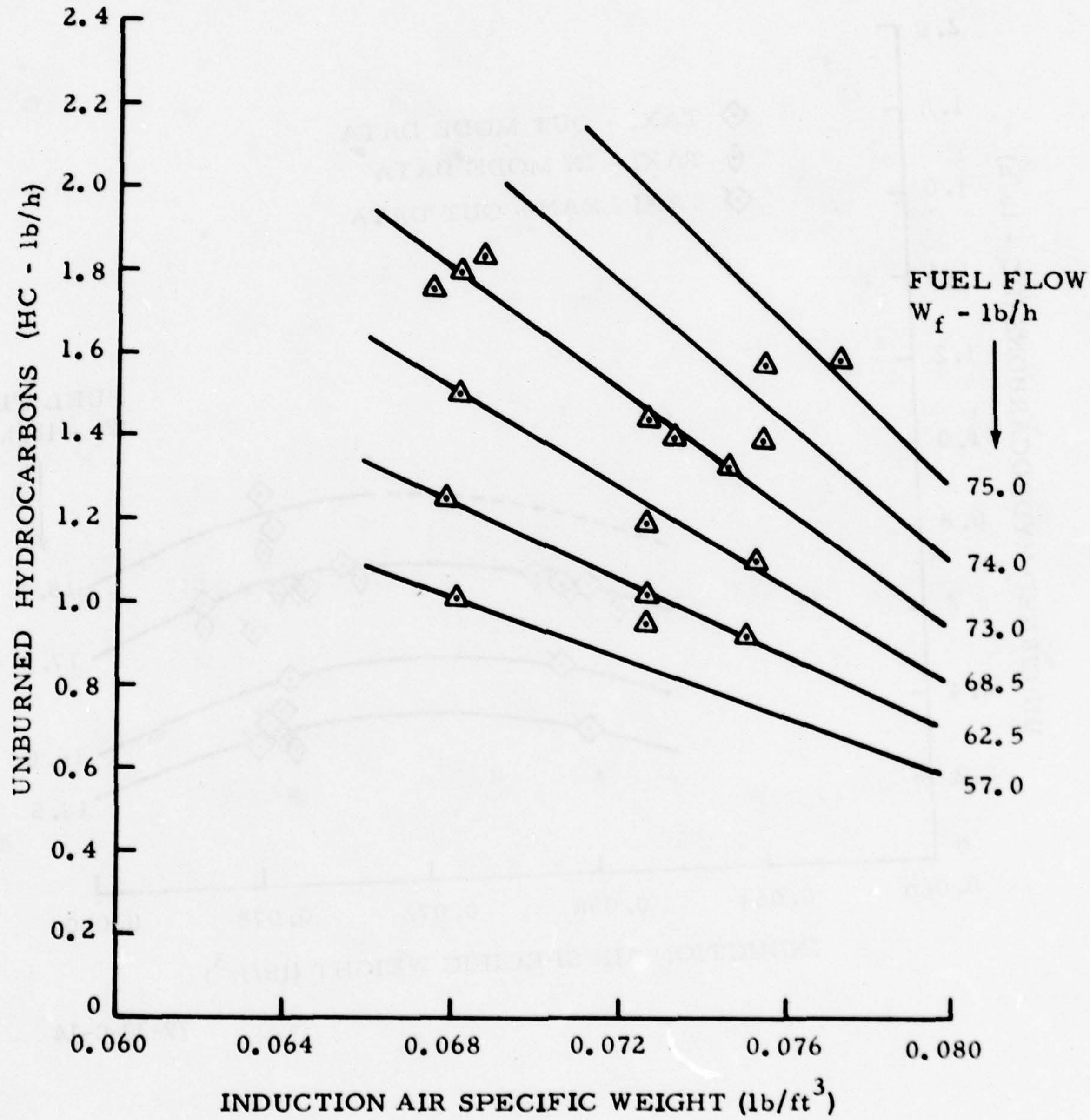


FIGURE C-12. UNBURNED EXHAUST HYDROCARBONS AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL CLIMB MODE CONSTANT FUEL FLOW SCHEDULES--TCM 6-285-B (TIARA) ENGINE



79-30-C-13

FIGURE C-13. UNBURNED EXHAUST HYDROCARBONS AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL APPROACH MODE CONSTANT FUEL FLOW SCHEDULES--TCM 6-285-B (TIARA) ENGINE

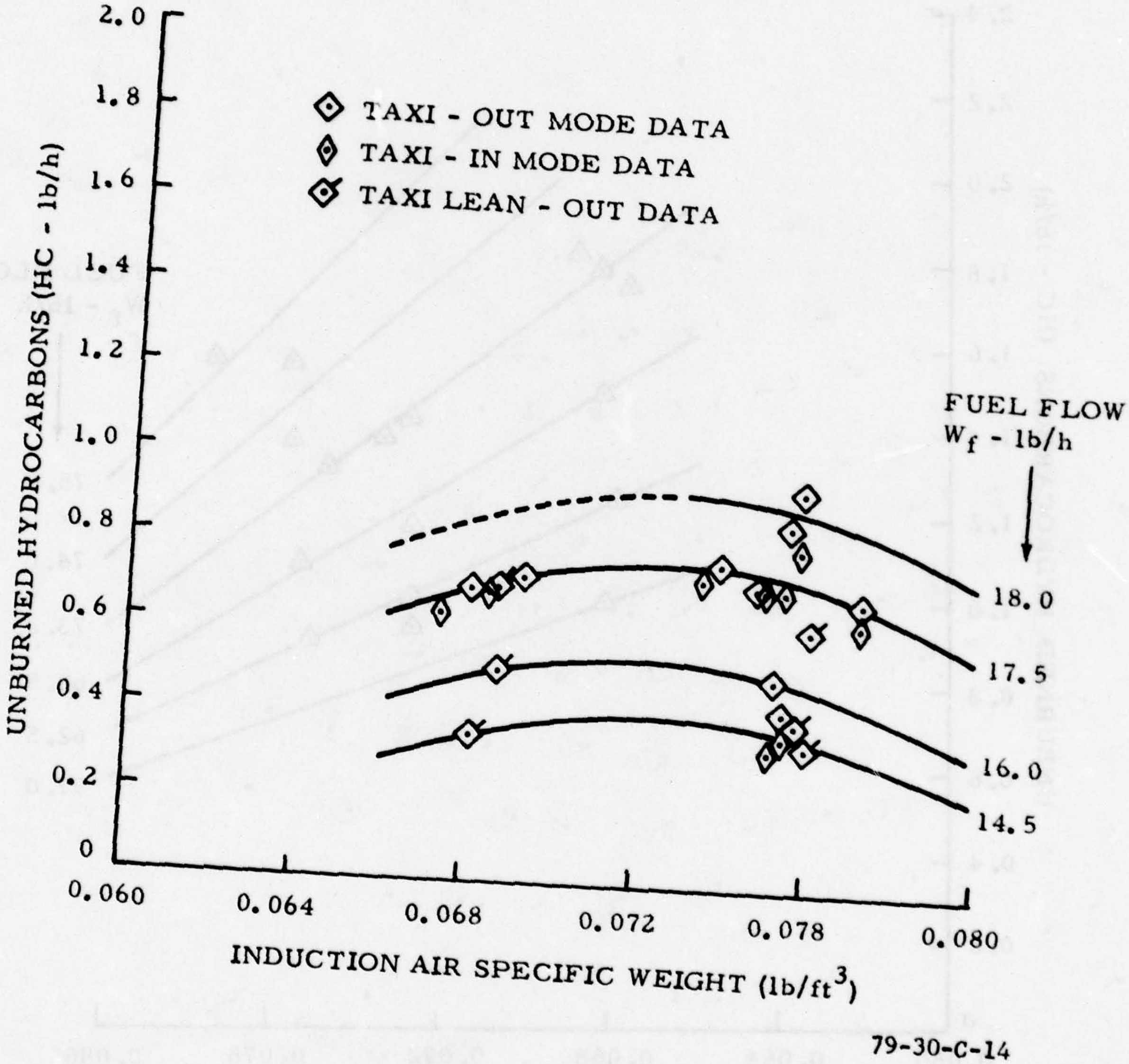


FIGURE C-14. UNBURNED EXHAUST HYDROCARBONS AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL TAXI MODE CONSTANT FUEL FLOW SCHEDULES--TCM 6-285-B (TIARA) ENGINE

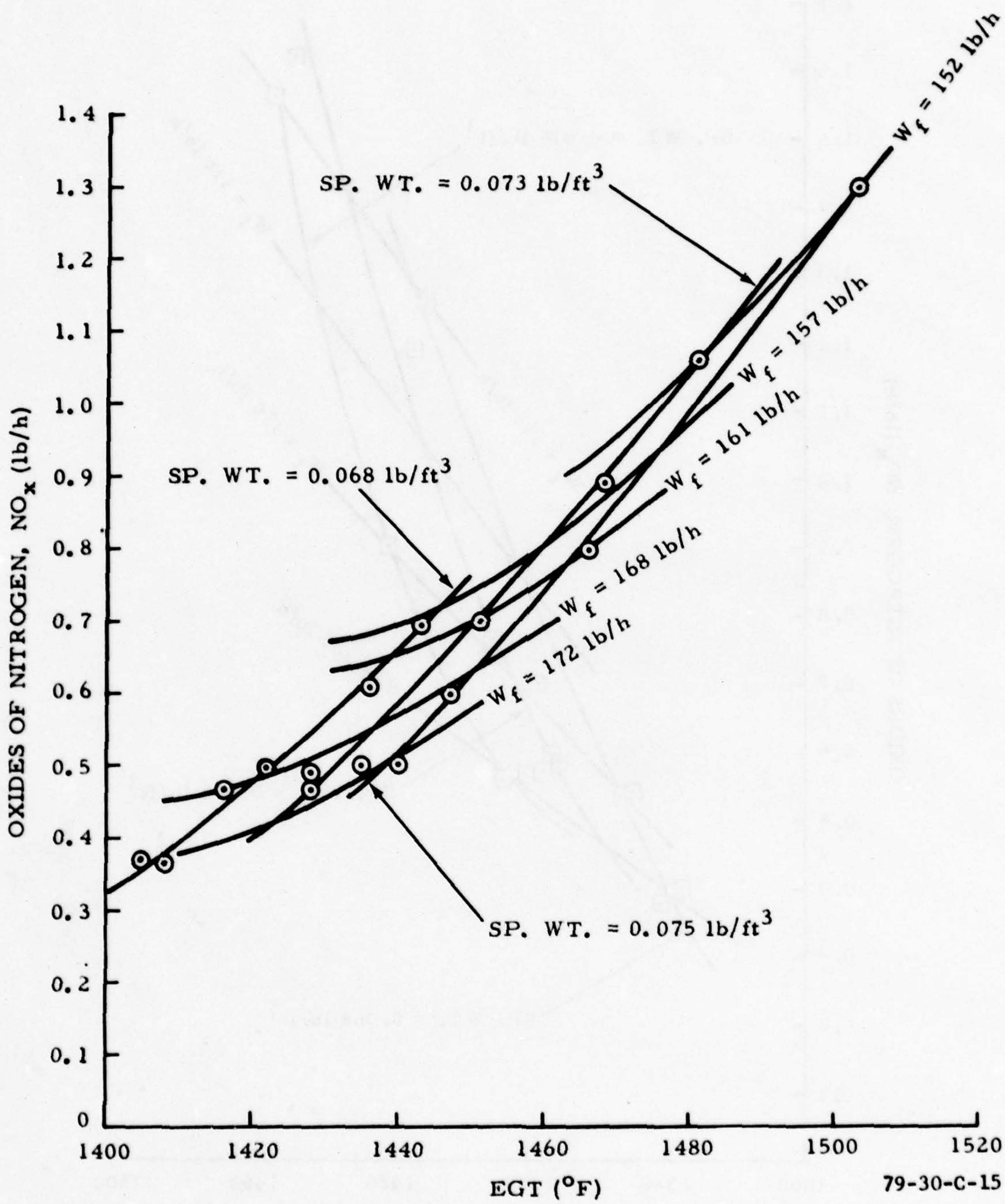


FIGURE C-15. OXIDES OF NITROGEN AS A FUNCTION OF EXHASUT GAS TEMPERATURE FOR SEVERAL TAKEOFF CONSTANT FUEL FLOW SCHEDULES AND DIFFERENT SPECIFIC WEIGHT CONDITIONS

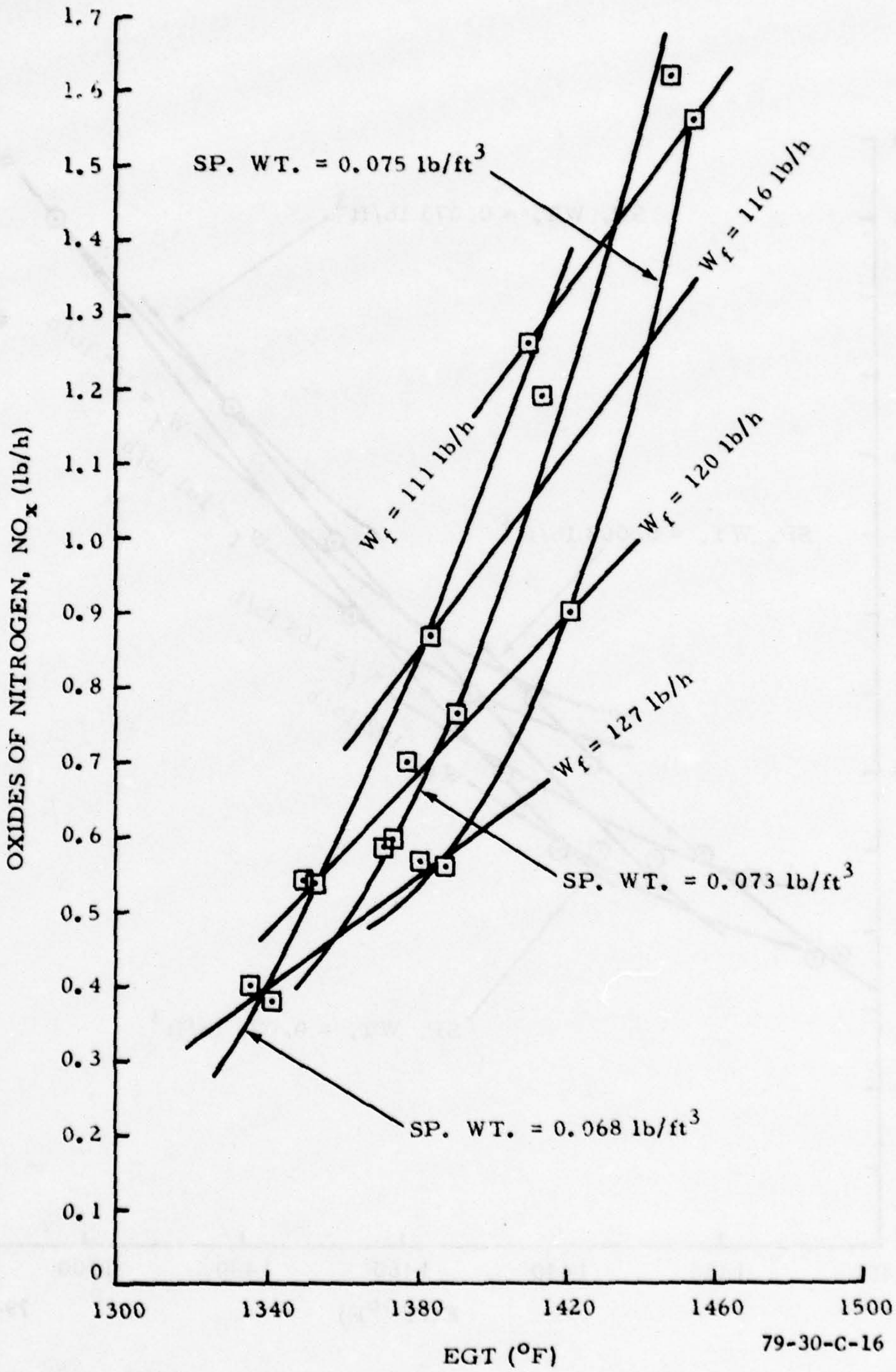
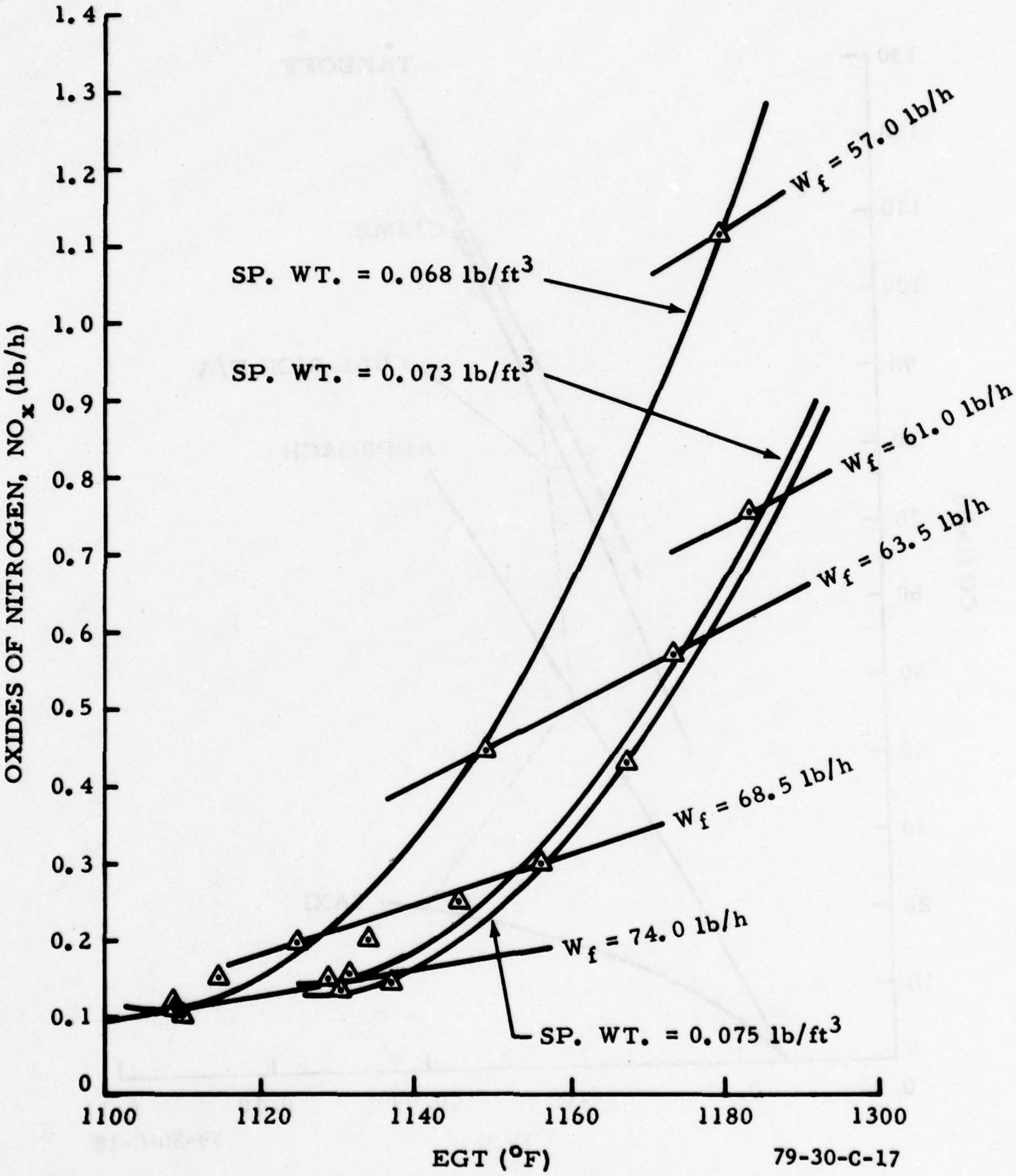


FIGURE C-16. OXIDES OF NOTROGEN AS A FUNCTION OF EXHAUST GAS TEMPERATURE FOR SEVERAL CLIMB MODE CONSTANT FUEL FLOW SCHEDULES AND DIFFERENT SPECIFIC WEIGHT CONDITIONS



79-30-C-17

FIGURE C-17. OXIDES OF NITROGEN AS A FUNCTION OF EXHAUST GAS TEMPERATURE FOR SEVERAL APPROACH MODE CONSTANT FLOW SCHEDULES AND DIFFERENT SPECIFIC WEIGHT CONDITIONS

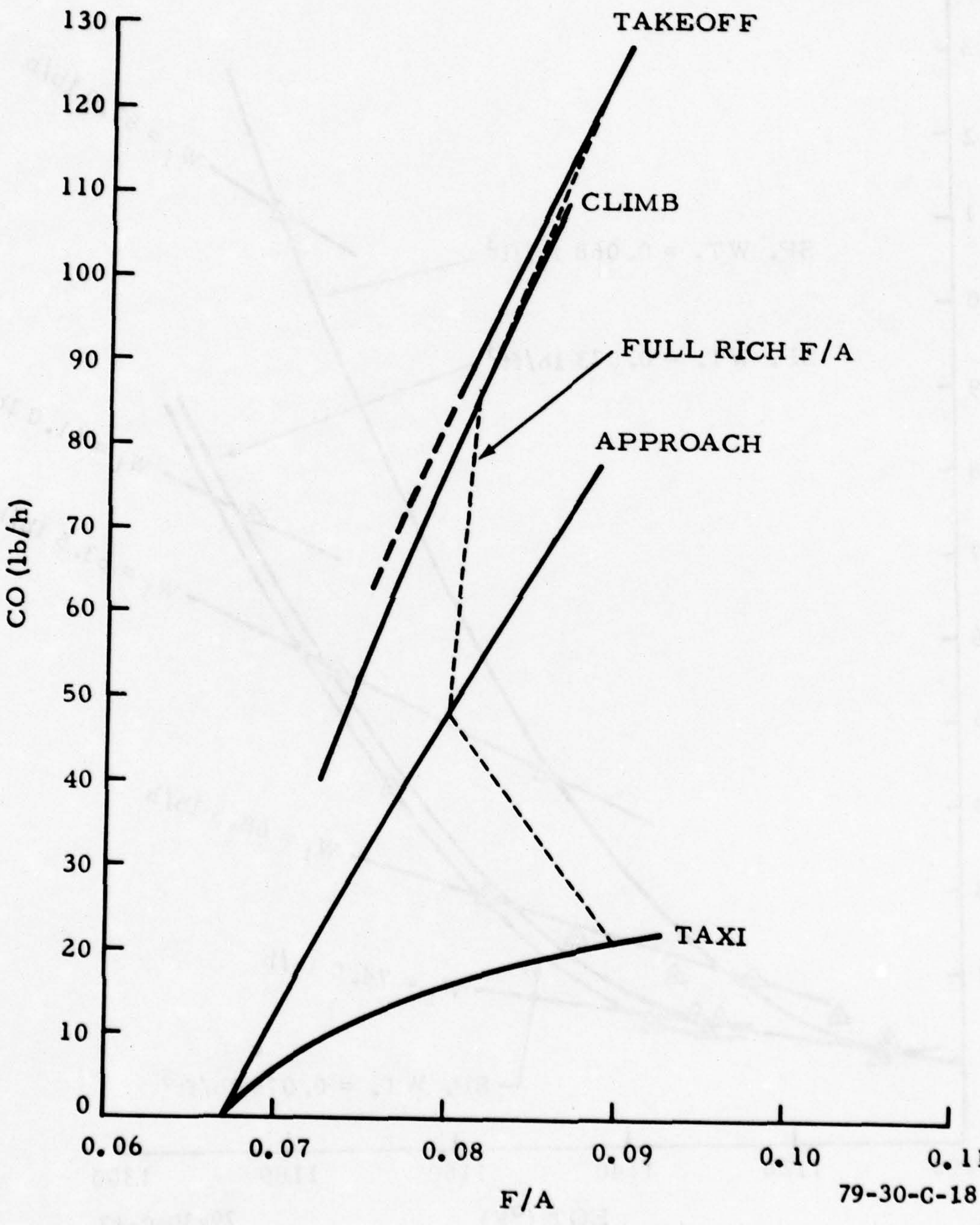


FIGURE C-18. SEA LEVEL STANDARD DAY EMISSION CHARACTERISTICS FOR A TCM 6-285-B (TIARA) ENGINE--CARBON MONOXIDE

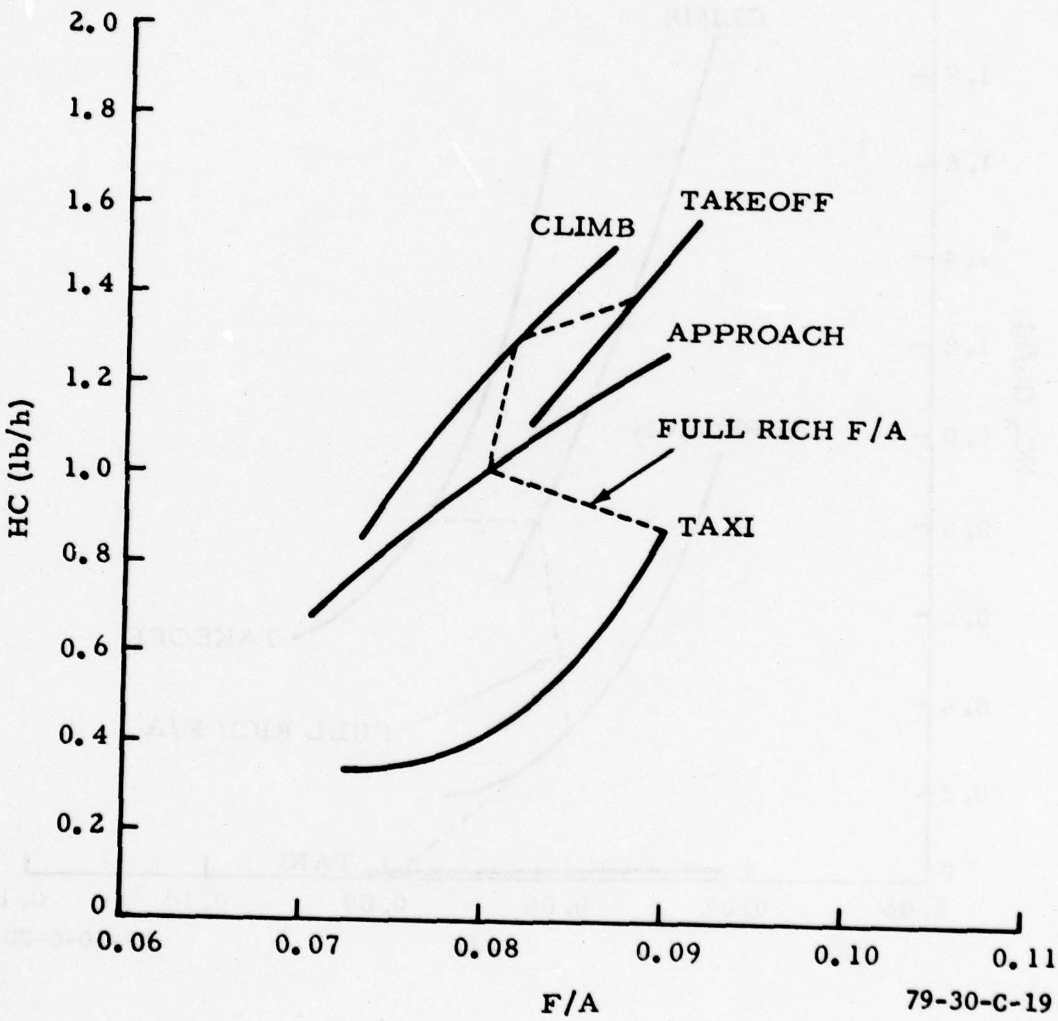


FIGURE C-19. SEA LEVEL STANDARD DAY EMISSIONS CHARACTERISTICS FOR A TCM 6-285-B (TIARA) ENGINE--UNBURNED HYDROCARBONS

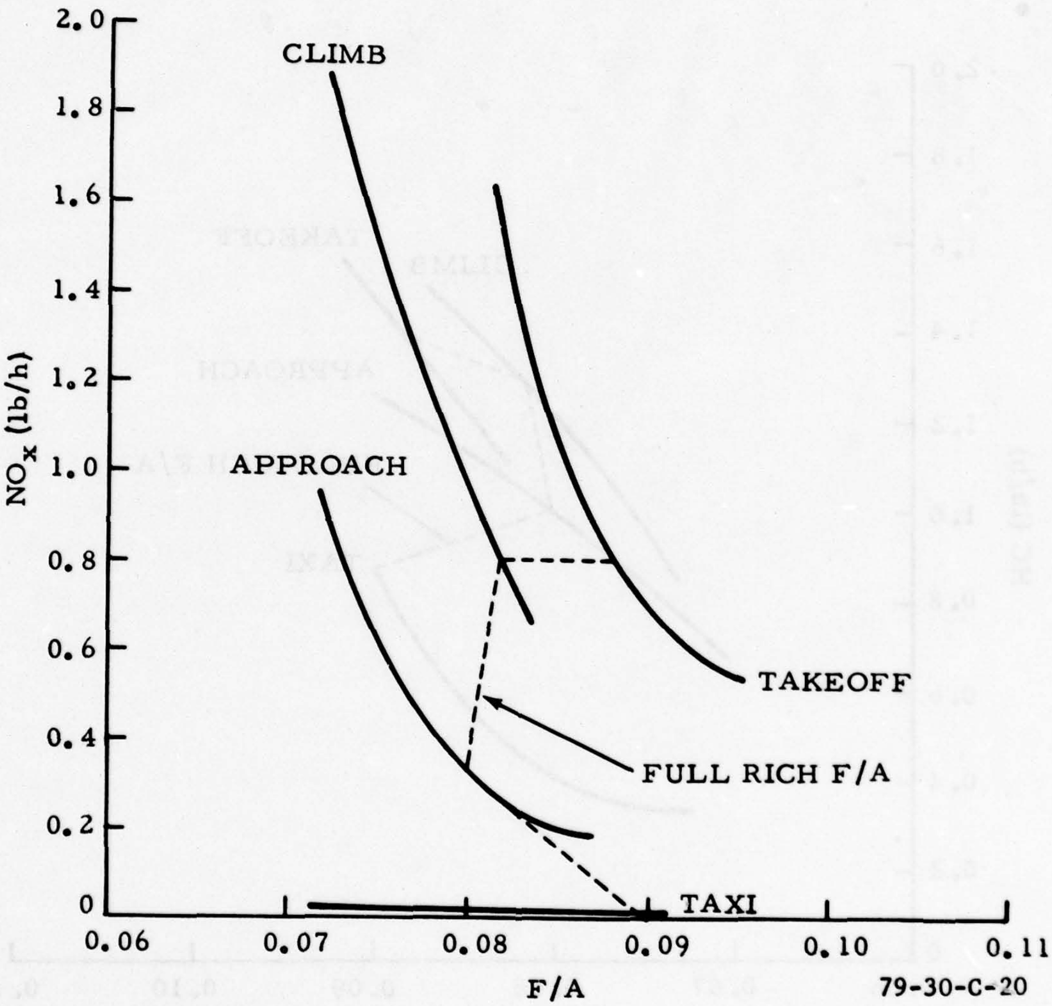


FIGURE C-20. SEA LEVEL STANDARD DAY EMISSIONS CHARACTERISTICS FOR A TCM 6-285-B (TIARA) ENGINE--OXIDES OF NITROGEN

TABLE C-1. TCM 6-285-B ENGINE NAFEC TEST DATA--BASELINE 1--
(NO IDLE, FIVE MODE) SPARK SETTING 30° BTC

	Parameter	Run No.	902	903	904	905	906
		Mode	Taxi Out	Takeoff	Climb	Approach	Taxi In
1.	Act. Baro. - inHgA		30.03	30.03	30.03	30.03	30.03
2.	Spec. Hum. - lb/lb		0.0150	0.0150	0.0150	0.0150	0.0150
3.	Induct. Air Temp.-°F		82	83	84	84	85
4.	Cooling Air Temp.-°F		91	86	86	88	88
5.	Induct. Air Press.-inHgA		30.17	29.96	30.11	30.03	30.20
6.	Engine Speed - RPM		1800	4000	3600	3500	1800
7.	Manifold Air Press.-inHgA		12.0	27.7	25.7	16.6	11.5
8.	Induct. Air Density-lb/ft^3		0.0738	0.0731	0.0731	0.0732	0.0734
9.	Fuel Flow, Wf-lb/h		17.3	166.0	124.0	74.0	16.5
10.	Airflow, W_a-lb/h		205.0	1767.0	1452.0	824.0	189.0
11.	F/A (Measured) = 9 / 10		0.0844	0.0939	0.0854	0.0898	0.0873
12.	Max. Cht - °F		405	444	430	375	372
13.	Avg. Cht - °F		373	427	418	365	351
14.	Min. Cht - °F		283	405	410	361	298
15.	EGT - °F		728	1428	1372	1158	739
16.	Torque, lb-ft		--	620	575	275	25
17.	OBS. Bhp		--	236	197	92	4
18.	% CO_2 (Dry)		8.15	9.21	9.98	8.59	8.41
19.	% CO (Dry)		9.70	8.45	7.24	9.46	9.28
20.	% O_2 (Dry)		0.65	0.18	0.21	0.27	0.59
21.	HC-ppm (Wet)		5857	1589	1528	2606	5925
22.	NO_x-ppm (Wet)		44	226	336	149	45
23.	CO_2-lb/h		25.84	246.6	216.2	109.0	24.46
24.	CO-lb/h		19.57	144.0	99.8	76.4	17.18
25.	O_2-lb/h		1.50	3.50	3.31	2.49	1.25
26.	HC-lb/h		0.76	1.85	1.42	1.40	0.72
27.	NO_x-lb/h		0.011	0.49	0.58	0.15	0.010
28.	CO-lb/Mode		3.914	0.720	8.317	7.641	1.145
29.	HC-lb/Mode		0.153	0.009	0.118	0.140	0.048
30.	NO_x-lb/Mode		0.002	0.002	0.049	0.015	0.001

TABLE C-2. TCM 6-285-B ENGINE NAFEC TEST DATA--BASELINE 2--
(NO IDLE, FIVE MODE) SPARK SETTING 30° BTC

	Parameter	Run No. / Mode	29 Taxi Out	30 Takeoff	31 Climb	32 Approach	33 Taxi In
1.	Act. Baro. - inHgA		30.14	30.14	30.14	30.14	30.14
2.	Spec. Hum. - lb/lb		0.0150	0.0150	0.0150	0.0150	0.0150
3.	Induct. Air Temp.-°F		77	76	75	76	76
4.	Cooling Air Temp.-°F		86	78	77	78	78
5.	Induct. Air Press.-inHgA		30.28	30.07	30.22	30.14	30.29
6.	Engine Speed - RPM		1800	4000	3600	3460	1775
7.	Manifold Air Press.-inHgA		11.7	27.7	25.7	16.5	11.5
8.	Induct. Air Density-lb/ft^3		0.0747	0.0747	0.0748	0.0745	0.0749
9.	Fuel Flow, W_f-lb/h		18.2	168.0	128.0	74.0	17.7
10.	Airflow, W_2-lb/h		208.0	1793.0	1486.0	827.0	201.0
11.	F/A (Measured) = 9 / 10		0.0875	0.0937	0.0861	0.0895	0.0881
12.	Max. Cht - °F		373	439	417	358	393
13.	Avg. Cht - °F		347	424	407	348	362
14.	Min. Cht - °F		272	397	397	344	281
15.	EGT - °F		729	1435	1381	1161	750
16.	Torque, lb-ft		32	622	587	291	40
17.	Obs. Bhp		5	237	201	96	7
18.	% CO_2 (Dry)		8.45	9.37	10.2	8.60	8.42
19.	% CO (Dry)		9.34	8.33	7.14	9.39	9.22
20.	% O_2 (Dry)		0.64	0.27	0.27	0.32	0.68
21.	HC-ppm (Wet)		5290	1628	1524	2471	5399
22.	NO_x-ppm (Wet)		45	227	317	133	43
23.	CO_2-lb/h		27.13	252.9	221.7	109.4	25.00
24.	CO-lb/h		19.09	144.0	100.6	76.0	18.12
25.	O_2-lb/h		1.49	5.33	4.34	2.96	1.53
26.	HC-lb/h		0.71	1.92	1.45	1.33	0.70
27.	NO_x-lb/h		0.011	0.501	0.565	0.134	0.010
28.	CO-lb/Mode		3.817	0.720	8.381	7.603	1.208
29.	HC-lb/Mode		0.142	0.010	0.121	0.133	0.047
30.	NO_x-lb/Mode		0.002	0.003	0.047	0.013	0.001

TABLE C-3. TCM 6-285-B ENGINE NAFEC TEST DATA--BASELINE 3--(NO IDLE, FIVE MODE) SPARK SETTING 30° BTC

	Run No.	55	56	57	58	59
Parameter	Mode	Taxi Out	Takeoff	Climb	Approach	Taxi In
1. Act. Baro. - inHgA		30.21	30.21	30.21	30.21	30.21
2. Spec. Hum. - lb/lb		0.0130	0.0130	0.0130	0.0130	0.0130
3. Induct. Air Temp.-°F		74	73	73	73	74
4. Cooling Air Temp.-°F		79	75	75	75	75
5. Induct. Air Press.-inHgA		30.38	30.14	30.29	30.28	30.37
6. Engine Speed - RPM		1800	4000	3600	3460	1800
7. Manifold Air Press.-inHgA		11.6	27.7	25.7	16.5	11.5
8. Induct. Air Density-lb/ft^3		0.0754	0.0749	0.0753	0.0753	0.0754
9. Fuel Flow, W_f-lb/h		18.4	172.0	130.0	76.0	18.0
10. Airflow, W_a-lb/h		197.0	1809.0	1488.0	845.0	200.0
11. F/A (Measured) -9 / 10		0.0934	0.0951	0.0874	0.0899	0.0900
12. Max. Cht - °F		385	435	422	368	385
13. Avg. Cht - °F		356	419	414	357	356
14. Min. Cht - °F		273	394	398	352	276
15. EGT - °F		707	1440	1386	1174	742
16. Torque, lb-ft		33	632	602	308	48
17. Obs. Bhp		6	241	206	101	8
18. % CO_2 (Dry)		7.88	9.17	9.84	8.53	8.30
19. % CO (Dry)		9.85	8.23	7.11	9.25	9.29
20. % O_2 (Dry)		0.71	0.31	0.32	0.37	0.69
21. HC-ppm (Wet)		6593	1586	1550	2524	5402
22. NO_x-ppm (Wet)		38	224	312	141	43
23. CO_2-lb/h		24.14	250.8	218.1	110.8	25.56
24. CO-lb/h		19.20	143.3	100.3	76.5	18.21
25. O_2-lb/h		1.58	6.17	5.16	3.49	1.54
26. HC-lb/h		0.86	1.90	1.49	1.39	0.70
27. NO_x-lb/h		0.009	0.50	0.56	0.14	0.010
28. CO-lb/h		3.841	0.716	8.357	7.647	1.214
29. HC-lb/h		0.171	0.010	0.124	0.139	0.047
30. NO_x-lb/Mode		0.002	0.003	0.047	0.014	0.001

TABLE C-4. TCM 6-285-B ENGINE NAFEC TEST DATA--BASELINE 4--
(NO IDLE, FIVE MODE) SPARK SETTING 30° BTC

	Parameter	Mode	Taxi Out	Takeoff	Climb	Approach	Taxi In
		Run No.	62	63	64	65	66
1.	Act. Baro. - inHgA		30.16	30.16	30.16	30.16	30.16
2.	Spec. Hum. - lb/lb		0.0145	0.0145	0.0145	0.0145	0.0145
3.	Induct. Air Temp.-°F		75	74	74	75	75
4.	Cooling Air Temp.-°F		75	76	76	77	75
5.	Induct. Air Press.-inHgA		30.34	30.09	30.25	30.28	30.31
6.	Engine Speed - RPM		1775	4000	3600	3460	1825
7.	Manifold Air Press.-inHgA		11.3	27.7	25.7	16.5	11.1
8.	Induct. Air Density-lb/ft^3		0.0752	0.0747	0.0751	0.0750	0.0751
9.	Fuel Flow, W_f-lb/h		14.5	153.0	111.0	63.0	16.2
10.	Airflow, W_a-lb/h		192.0	1789.0	1456.0	820.0	206.0
11.	F/A (Measured) = 9 / 10		0.0755	0.0855	0.0762	0.0768	0.0786
12.	Max. Cht - °F		380	460	434	381	369
13.	Avg. Cht - °F		357	444	425	371	350
14.	Min. Cht - °F		283	418	412	366	292
15.	EGT - °F		730	1503	1454	1246	782
16.	Torque, lb-ft		34	620	600	303	50
17.	Obs. Bhp		6	236	206	100	9
18.	% CO_2 (Dry)		9.89	10.55	11.92	11.25	10.67
19.	% CO (Dry)		6.86	6.20	4.01	4.87	5.54
20.	% O_2 (Dry)		0.60	0.25	0.30	0.34	0.60
21.	HC-ppm (Wet)		4165	1213	1222	1804	2530
22.	NO_x-ppm (Wet)		63	607	923	597	84
23.	CO_2-lb/h		28.23	277.8	249.5	133.6	32.18
24.	CO-lb/h		12.46	103.9	53.4	36.8	10.63
25.	O_2-lb/h		1.25	4.79	4.57	2.94	1.32
26.	HC-lb/h		0.49	1.39	1.10	0.92	0.33
27.	NO_x-lb/h		0.014	1.30	1.56	0.57	0.020
28.	CO-lb/Mode		2.492	0.520	4.452	3.682	0.709
29.	HC-lb/Mode		0.099	0.007	0.092	0.092	0.022
30.	NO_x-lb/Mode		0.003	0.006	0.130	0.057	0.001

TABLE C-5. TCM 6-285-B ENGINE NAFEC TEST DATA--Baseline 5--(NO IDLE, FIVE MODE) SPARK SETTING 30° BTC

	Parameter	Mode	Taxi Out	Takeoff	Climb	Approach	Taxi In
		Run No.	69	70	71	72	73
1.	Act. Baro. - inHgA		30.20	30.20	30.20	30.20	30.20
2.	Spec. Hum. - lb/lb		0.0130	0.0130	0.0130	0.0130	0.0130
3.	Induct. Air Temp.-°F		74	73	73	73	74
4.	Cooling Air Temp.-°F		80	74	74	74	76
5.	Induct. Air Press.-inHgA		30.36	30.13	30.28	30.24	30.38
6.	Engine Speed - RPM		1825	4000	3600	3500	1800
7.	Manifold Air Press.-inHgA		11.4	27.7	25.7	16.5	11.1
8.	Induct. Air Density-lb/ft3		0.0754	0.0749	0.0753	0.0752	0.0754
9.	Fuel Flow, W_f-lb/h		15.8	160.0	120.0	70.0	14.7
10.	Airflow, W_a-lb/h		201.6	1808.6	1487.7	844.5	194.9
11.	F/A (Measured) = 9 / 10		0.0784	0.0885	0.0807	0.0829	0.0754
12.	Max. Cht - °F		372	446	427	373	367
13.	Avg. Cht - °F		348	428	419	364	351
14.	Min. Cht - °F		281	405	406	360	301
15.	EGT - °F		702	1466	1421	1212	772
16.	Torque, lb-ft		46	625	605	307	41
17.	Obs. Bhp		8	238	207	102	7
18.	% CO_2 (Dry)		9.96	9.97	10.66	9.84	10.22
19.	% CO (Dry)		6.45	6.66	5.52	6.86	5.95
20.	% O_2 (Dry)		0.58	0.24	0.26	0.34	0.62
21.	HC-ppm (Wet)		3311	1409	1380	2054	2067
22.	NO_x-ppm (Wet)		75	365	514	301	72
23.	CO_2-lb/h		29.66	271.5	238.4	123.4	29.25
24.	CO-lb/h		12.23	118.0	80.7	54.7	10.84
25.	O_2-lb/h		1.26	4.69	4.13	3.10	1.29
26.	HC-lb/h		0.42	1.65	1.29	1.10	0.36
27.	NO_x-lb/h		0.018	0.80	0.90	0.301	0.016
28.	CO-lb/Mode		2.445	0.566	6.727	5.467	0.722
29.	HC-lb/Mode		0.083	0.008	0.108	0.110	0.024
30.	NO_x-lb/Mode		0.004	0.004	0.075	0.030	0.001

TABLE C-6. TCM 6-285-B ENGINE NAFEC TEST DATA--BASELINE 6--
(NO IDLE, FIVE MODE) SPARK SETTING 30° BTC

	Parameter	Run No. / Mode	76 Taxi Out	77 Takeoff	78 Climb	79 Approach	80 Taxi In
1.	Act. Baro. - inHgA		30.16	30.16	30.16	30.16	30.16
2.	Spec. Hum. - lb/lb		0.0090	0.0090	0.0090	0.0090	0.0090
3.	Induct. Air Temp.-°F		71	71	71	72	71
4.	Cooling Air Temp.-°F		70	72	72	71	70
5.	Induct. Air Press.-inHgA		30.33	30.08	30.23	30.27	30.33
6.	Engine Speed - RPM		1800	4000	3600	3460	1800
7.	Manifold Air Press.-inHgA		11.1	27.8	25.7	16.5	11.0
8.	Induct. Air Density-lb/ft^3		0.0757	0.0751	0.0755	0.0754	0.0757
9.	Fuel Flow, W_f-lb/h		17.6	172.0	128.0	75.0	17.8
10.	Airflow, W_a-lb/h		198.0	1811.0	1482.0	859.0	199.0
11.	F/A (Measured) = 9 / 10		0.0889	0.0950	0.0864	0.0873	0.0894
12.	Max. Cht - °F		395	419	401	349	356
13.	Avg. Cht - °F		364	400	393	342	335
14.	Min. Cht - °F		274	380	385	338	273
15.	EGT - °F		714	1447	1378	1168	735
16.	Torque, lb-ft		38	645	608	300	44
17.	Obs. Bhp		7	246	208	99	8
18.	% CO_2 (Dry)		8.35	9.52	10.26	8.87	8.40
19.	% CO (Dry)		10.23	8.83	7.58	10.05	10.33
20.	% O_2 (Dry)		0.63	0.20	0.25	0.30	0.65
21.	HC-ppm (Wet)		7366	1923	1911	2840	5810
22.	NO_x-ppm (Wet)		56	254	393	195	52
23.	CO_2-lb/h		26.2	266.2	230.6	120.3	26.5
24.	CO-lb/h		20.4	157.1	108.4	86.8	20.8
25.	O_2-lb/h		1.4	4.1	4.1	3.0	1.5
26.	HC-lb/h		0.94	2.3	1.8	1.57	0.8
27.	NO_x-lb/h		0.01	0.6	0.7	0.2	0.01
28.	CO-lb/Mode		4.078	0.786	9.036	8.676	1.384
29.	HC-lb/Mode		0.189	0.012	0.151	0.157	0.050
30.	NO_x-lb/Mode		0.003	0.003	0.058	0.020	0.001

TABLE C-7. TCM 6-285-B ENGINE NAFEC TEST DATA--BASELINE 7--
(NO IDLE, FIVE MODE) SPARK SETTING 30° BTC

Parameter	Run No.	101	102	103	104	105
	Mode	Taxi Out	Takeoff	Climb	Approach	Taxi In
1. Act. Baro. - inHgA		29.93	29.93	29.93	29.93	29.93
2. Spec. Hum. - lb/lb		0.0080	0.0080	0.0080	0.0080	0.0080
3. Induct. Air Temp.-°F		67	66	66	66	67
4. Cooling Air Temp.-°F		61	63	63	63	62
5. Induct. Air Press.-inHgA		30.27	30.16	30.21	30.21	30.27
6. Engine Speed - RPM		1800	4000	3620	3460	1775
7. Manifold Air Press.-inHgA		11.1	27.7	25.7	16.4	11.1
8. Induct. Air Density-lb/ft^3		0.0761	0.0760	0.0761	0.0761	0.0761
9. Fuel Flow, W_f-lb/h		16.3	175.0	130.0	75.0	16.3
10. Airflow, W_a-lb/h		206.0	1818.0	1495.0	831.0	198.0
11. F/A (Measured) = 9 / 10		0.0791	0.0963	0.0870	0.0903	0.0823
12. Max. Cht - °F		369	415	407	339	337
13. Avg. Cht - °F		339	399	395	332	324
14. Min. Cht - °F		276	379	383	327	285
15. EGT - °F		721	1426	1378	1147	765
16. Torque, lb-ft		50	640	613	313	50
17. Obs. Bhp		9	244	211	103	8
18. % CO_2 (Dry)		9.08	9.14	10.19	8.75	8.84
19. % CO (Dry)		8.58	9.13	7.57	9.95	9.26
20. % O_2 (Dry)		0.57	0.21	0.24	0.30	0.62
21. HC-ppm (Wet)		6330	1860	1836	2830	5549
22. NO_x-ppm (Wet)		56	213	348	162	48
23. CO_2-lb/h		28.5	255.6	229.9	113.2	27.1
24. CO-lb/h		17.1	162.5	108.7	81.9	18.0
25. O_2-lb/h		1.30	4.27	3.94	2.82	1.38
26. HC-lb/h		0.814	2.25	1.77	1.53	0.696
27. NO_x-lb/h		0.014	0.48	0.63	0.16	0.011
28. CO-lb/Mode		3.429	0.812	9.957	8.194	1.203
29. HC-lb/Mode		0.163	0.011	0.147	0.153	0.046
30. NO_x-lb/Mode		0.003	0.002	0.052	0.016	0.001

TABLE C-8. TCM 6-285-B ENGINE NAFEC TEST DATA--BASELINE 8--(NO IDLE, FIVE MODE) SPARK SETTING 30° BTC

Parameter	Run No.	114	115	116	117	118
	Mode	Taxi Out	Takeoff	Climb	Approach	Taxi In
1. Act. Baro. - inHgA		30.06	30.06	30.06	30.06	30.06
2. Spec. Hum. - lb/lb		0.0060	0.0060	0.0060	0.0060	0.0060
3. Induct. Air Temp.-°F		62	61	61	61	62
4. Cooling Air Temp.-°F		57	58	58	58	57
5. Induct. Air Press.-inHgA		30.41	30.30	30.35	30.35	30.41
6. Engine Speed - RPM		1820	4000	3600	3480	1820
7. Manifold Air Press.-inHgA		10.9	27.7	25.7	16.4	10.9
8. Induct. Air Density-lb/ft^3		0.0772	0.0771	0.0772	0.0772	0.0772
9. Fuel Flow, W_f-lb/h		17.2	174.0	132.0	75.0	17.4
10. Airflow, W_a-lb/h		205.0	1811.0	1514.0	856.0	202.0
11. F/A (Measured) = 9 / 10		0.0839	0.0961	0.0872	0.0876	0.0861
12. Max. Cht - °F		366	413	395	347	351
13. Avg. Cht - °F		340	394	388	340	333
14. Min. Cht - °F		277	374	378	335	281
15. EGT - °F		740	1432	1386	1160	737
16. Torque, lb-ft		--	634	598	285	4
17. Obs. Bhp		--	241	205	94	—
18. % CO_2 (Dry)		8.71	9.37	10.18	8.79	9.21
19. % CO (Dry)		9.95	9.28	7.90	10.50	9.52
20. % O_2 (Dry)		0.58	0.19	0.23	0.28	0.62
21. HC-ppm (Wet)		5227	1845	1777	2869	4832
22. NO_x-ppm (Wet)		62	238	372	181	63
23. CO_2-lb/h		28.0	263.4	234.6	119.3	29.2
24. CO lb/h		20.4	166.0	115.9	90.7	19.2
25. O_2-lb/h		1.36	3.88	3.85	2.76	1.43
26. HC-lb/h		0.68	2.22	1.73	1.58	0.63
27. NO_x-lb/h		0.015	0.54	0.68	0.19	0.015
28. CO-lb/Mode		4.080	0.830	9.658	9.000	1.280
29. HC-lb/Mode		0.136	0.011	0.144	0.158	0.042
30. NO_x-lb/Mode		0.003	0.003	0.056	0.019	0.001

TABLE C-9. TCM 6-285-B ENGINE NAFEC TEST DATA--BASELINE 9--
(NO IDLE, FIVE MODE) SPARK SETTING 30° BTC

	Run No.	120	121	122	123	124
Parameter	**Mode**	**Taxi Out**	**Takeoff**	**Climb**	**Approach**	**Taxi In**
1. Act. Baro. - inHgA		29.92	29.92	29.92	29.92	29.92
2. Spec. Hum. - lb/lb		0.0095	0.0095	0.0095	0.0095	0.0095
3. Induct. Air Temp.-°F		113	122	125	123	119
4. Cooling Air Temp.-°F		124	123	127	126	121
5. Induct. Air Press.-inHgA		29.93	30.15	30.32	30.22	29.93
6. Engine Speed - RPM		1800	4000	3600	3375	1800
7. Manifold Air Press.-inHgA		11.3	27.9	25.7	16.5	11.2
8. Induct. Air Density-lb/ft^3		0.0692	0.0687	0.0687	0.0687	0.0685
9. Fuel Flow, W_f-lb/h		16.8	172.0	126.0	72.0	17.2
10. Airflow, W_a-lb/h		204.0	1755.0	1428.0	785.0	203.0
11. F/A (Measured) = 9 / 10		0.0824	0.0980	0.0882	0.0917	0.0847
12. Max. Cht - °F		302	451	431	385	324
13. Avg. Cht - °F		296	432	427	381	319
14. Min. Cht - °F		290	414	418	375	310
15. EGT - °F		707	1408	1342	1120	741
16. Torque, lb-ft		20	600	552	258	26
17. Obs. Bhp		3	228	189	83	4
18. % CO_2 (Dry)		8.77	8.66	9.27	7.93	8.69
19. % CO (Dry)		8.61	9.27	8.32	10.31	8.69
20. % O_2 (Dry)		0.59	0.20	0.22	0.29	0.59
21. HC-ppm (Wet)		5548	2290	2136	3562	5272
22. NO_x-ppm (Wet)		45	166	219	106	41
23. CO_2-lb/h		27.35	234.3	201.5	97.5	26.99
24. CO-lb/h		17.09	159.6	115.1	80.7	17.18
25. O_2-lb/h		1.34	3.93	3.48	2.59	1.33
26. HC-lb/h		0.72	2.69	1.97	1.83	0.683
27. NO_x-lb/h		0.011	0.365	0.378	0.102	0.0099
28. CO-lb/Mode		3.418	0.798	9.591	8.070	1.145
29. HC-lb/Mode		0.143	0.013	0.164	0.183	0.046
30. NO_x-lb/Mode		0.002	0.002	0.032	0.010	0.001

TABLE C-10. TCM 6-285-B ENGINE NAFEC TEST DATA--BASELINE 10--
(NO IDLE, FIVE MODE) SPARK SETTING 30° BTC

	Parameter	Mode	Taxi Out	Takeoff	Climb	Approach	Taxi In
		Run No.	135	136	137	138	139
1.	Act. Baro. - inHgA		28.50	28.50	28.50	28.50	28.40
2.	Spec. Hum. - lb/lb		0.0110	0.0110	0.0110	0.0110	0.0110
3.	Induct. Air Temp.-°F		103	109	112	106	104
4.	Cooling Air Temp.-°F		113	110	113	105	110
5.	Induct. Air Press.-inHgA		28.88	29.07	29.14	28.83	28.62
6.	Engine Speed - RPM		1810	4000	3600	3375	1800
7.	Manifold Air Press.-inHgA		11.3	28.0	25.7	16.5	11.3
8.	Induct. Air Density-lb/ft^3		0.0680	0.0677	0.0675	0.0675	0.0673
9.	Fuel Flow, W_f-lb/h		17.8	174.0	126.0	72.0	17.6
10.	Airflow, W_a-lb/h		212.0	1742.0	1391.0	787.0	204.0
11.	F/A (Measured) = 9 / 10		0.0840	0.0999	0.0906	0.0915	0.0863
12.	Max. Cht - °F		300	441	422	362	306
13.	Avg. Cht - °F		294	419	417	358	299
14.	Min. Cht - °F		288	401	407	354	291
15.	EGT - °F		743	1416	1350	1129	732
16.	Torque, lb-ft		--	605	550	268	30
17.	Obs. Bhp		--	230	188	86	5
18.	% CO_2 (Dry)		9.28	8.75	9.40	8.12	9.02
19.	% CO (Dry)		7.89	8.99	7.84	9.66	7.95
20.	% O_2 (Dry)		0.59	0.20	0.22	0.30	0.59
21.	HC-ppm (Wet)		5110	2105	2010	3400	4796
22.	NO_x-ppm (Wet)		69	214	316	158	60
23.	CO_2-lb/h		29.5	234.3	195.6	98.2	27.6
24.	CO-lb/h		16.0	153.2	103.8	74.4	15.5
25.	O_2-lb/h		1.37	3.89	3.33	2.64	1.32
26.	HC-lb/h		0.69	2.47	1.82	1.75	0.63
27.	NO_x-lb/h		0.017	0.47	0.54	0.15	0.015
28.	CO-lb/Mode		3.197	0.766	8.654	7.438	1.034
29.	HC-lb/Mode		0.138	0.012	0.152	0.175	0.042
30.	NO_x-lb/Mode		0.004	0.002	0.045	0.015	0.001

TABLE C-11 TCM 6-285-B ENGINE NAFEC TEST DATA--TAKEOFF MODE LEAN-OUT--SPARK SETTING 30° BTC

	Parameter	Mode	Run No. 8	9	10	11
			Takeoff	Takeoff	Takeoff	Takeoff
1.	Act. Baro. - inHgA		30.04	30.04	30.03	30.04
2.	Spec. Hum. - lb/lb		0.0140	0.0140	0.0140	0.0140
3.	Induct. Air Temp.-°F		85	85	85	85
4.	Cooling Air Temp.-°F		87	88	88	88
5.	Induct. Air Press.-inHgA		29.97	29.96	29.96	29.96
6.	Engine Speed - RPM		4000	4000	4000	4000
7.	Manifold Air Press.-inHgA		27.7	27.7	27.7	27.7
8.	Induct. Air Density-lb/ft^3		0.0729	0.0729	0.0729	0.0729
9.	Fuel Flow, W_f-lb/h		165.0	160.0	155.0	150.0
10.	Airflow, W_a-lb/h		1761.0	1756.0	1758.0	1763.0
11.	F/A (Measured) = 9 / 10		0.0937	0.0911	0.0882	0.0851
12.	Max. Cht - °F		449	456	466	469
13.	Avg. Cht - °F		432	439	446	452
14.	Min. Cht - °F		410	415	421	426
15.	EGT - °F		1428	1451	1468	1481
16.	Torque, lb-ft		615	610	612	612
17.	Obs. Bhp		234	232	233	233
18.	% CO_2 (Dry)		9.40	9.78	10.22	10.62
19.	% CO (Dry)		8.00	7.46	6.71	6.11
20.	% O_2 (Dry)		0.15	0.17	0.19	0.22
21.	HC-ppm (Wet)		1309	1432	1348	1372
22.	NO_x-ppm (Wet)		215	326	419	502
23.	CO_2-lb/h		249.1	256.9	266.1	275.4
24.	CO-lb/h		135.0	124.7	111.2	100.8
25.	O_2-lb/h		2.89	3.25	3.50	4.15
26.	HC-lb/h		1.52	1.64	1.53	1.55
27.	NO_x-lb/h		0.47	0.70	0.89	1.06
28.	CO-lb/Mode		0.675	0.624	0.556	0.504
29.	HC-lb/Mode		0.008	0.008	0.008	0.008
30.	NO_x-lb/Mode		0.002	0.003	0.004	0.005

TABLE C-12. TCM 6-285-B ENGINE NAFEC TEST DATA--CLIMB MODE
LEAN-OUT--SPARK SETTING 30° BTC

	Parameter	Mode	12	13	14	15
		Run No.	12	13	14	15
			Climb	Climb	Climb	Climb
1.	Act. Baro. - inHgA		30.04	30.04	30.04	30.03
2.	Spec. Hum. - lb/lb		0.0140	0.0140	0.0140	0.0140
3.	Induct. Air Temp.-°F		86	86	86	86
4.	Cooling Air Temp.-°F		89	88	89	89
5.	Induct. Air Press.-inHgA		30.12	30.12	30.12	30.12
6.	Engine Speed - RPM		3600	3600	3600	3600
7.	Manifold Air Press.-inHgA		25.7	25.6	25.6	25.7
8.	Induct. Air Density-lb/ft^3		0.0731	0.0731	0.0731	0.0731
9.	Fuel Flow, W_f-lb/h		123.0	118.0	113.0	108.0
10.	Airflow, W_a-lb/h		1429.0	1434.0	1440.0	1437.0
11.	F/A (Measured) = 9 / 10		0.0861	0.0823	0.0785	0.0752
12.	Max. Cht - °F		434	432	437	442
13.	Avg. Cht - °F		421	421	426	432
14.	Min. Cht - °F		412	414	419	424
15.	EGT - °F		1374	1391	1414	1448
16.	Torque, lb-ft		556	559	557	554
17.	Obs. Bhp		191	192	191	190
18.	% CO_2 (Dry)		9.85	10.34	11.15	11.74
19.	% CO (Dry)		7.12	6.33	5.01	4.12
20.	% O_2 (Dry)		0.21	0.21	0.24	0.25
21.	HC-ppm (Wet)		1550	1475	1342	1251
22.	NO_x-ppm (Wet)		346	452	706	980
23.	CO_2-lb/h		209.2	218.4	232.8	242.4
24.	CO-lb/h		96.3	85.1	66.6	54.1
25.	O_2-lb/h		3.24	3.22	3.64	3.75
26.	HC-lb/h		1.42	1.34	1.20	1.11
27.	NO_x-lb/h		0.59	0.77	1.19	1.62
28.	CO-lb/Mode		8.022	7.091	5.547	4.511
29.	HC-lb/Mode		0.118	0.111	0.100	0.092
30.	NO_x-lb/Mode		0.049	0.064	0.099	0.135

TABLE C-13. TCM 6-285-B ENGINE NAFEC TEST DATA--APPROACH MODE
LEAN-OUT--SPARK SETTING 30° BTC

	Parameter	Run No.	16	17	18	19
		Mode	Approach	Approach	Approach	Approach
1.	Act. Baro. - inHgA		30.00	30.00	30.00	30.00
2.	Spec. Hum. - lb/lb		0.0130	0.0130	0.0130	0.0130
3.	Induct. Air Temp.-°F		88	88	88	88
4.	Cooling Air Temp.-°F		91	92	91	92
5.	Induct. Air Press.-inHgA		30.00	30.00	30.00	30.00
6.	Engine Speed - RPM		3490	3480	3480	3480
7.	Manifold Air Press.-inHgA		16.5	16.5	16.5	16.5
8.	Induct. Air Density-lb/ft^3		0.0726	0.0726	0.0726	0.0726
9.	Fuel Flow, W_f-lb/h		74.0	69.0	64.0	61.0
10.	Airflow, W_a-lb/h		825.0	811.0	816.0	825.0
11.	F/A (Measured) = 9 / 10		0.0897	0.0851	0.0784	0.0739
12.	Max. Cht - °F		363	371	385	390
13.	Avg. Cht - °F		356	362	375	380
14.	Min. Cht - °F		351	358	370	374
15.	EGT - °F		1163	1191	1234	1266
16.	Torguw, lb-ft		264	265	267	264
17.	Obs. Bhp		88	88	88	87
18.	% CO_2 (Dry)		8.43	9.40	10.45	11.58
19.	% CO (Dry)		9.25	7.55	5.81	4.07
20.	% O2 (Dry)		0.24	0.27	0.25	0.28
21.	HC-ppm (Wet)		2687	2297	2012	1879
22.	NO_x-ppm (Wet)		153	258	454	797
23.	CO_2-lb/h		106.5	114.0	124.5	137.1
24.	CO-lb/h		74.4	58.3	44.1	30.7
25.	O_2-lb/h		2.20	2.38	2.17	2.41
26.	HC-lb/h		1.44	1.19	1.02	0.95
27.	NO_x-lb/h		0.15	0.25	0.43	0.75
28.	CO-lb/Mode		7.439	5.827	4.405	3.066
29.	HC-lb/Mode		0.144	0.119	0.102	0.095
30.	NO_x-lb/Mode		0.015	0.025	0.043	0.075

TABLE C-14. TCM 6-285-B ENGINE NAFEC TEST DATA--TAKEOFF MODE
LEAN-OUT--SPARK SETTING 30° BTC

Parameter	Run No.	42	43	44	45
	Mode	Takeoff	Takeoff	Takeoff	Takeoff
1. Act. Baro. - inHgA		29.93	29.93	29.93	29.93
2. Spec. Hum. - lb/lb		0.0100	0.0100	0.0100	0.0100
3. Induct. Air Temp.-°F		121	125	127	128
4. Cooling Air Temp.-°F		128	129	129	130
5. Induct. Air Press.-inHgA		30.15	30.15	30.15	30.15
6. Engine Speed - RPM		4000	4000	4000	4000
7. Manifold Air Press.-inHgA		27.9	27.9	27.9	27.9
8. Induct. Air Density-lb/ft^3		0.0688	0.0683	0.0681	0.0680
9. Fuel Flow, W_f-lb/h		174.0	169.0	164.0	159.0
10. Airflow, W_a-lb/h		1758.0	1749.6	1745.0	1737.6
11. F/A (Measured) = 9 / 10		0.0990	0.0966	0.0940	0.0915
12. Max. Cht - °F		449	459	468	476
13. Avg. Cht - °F		429	439	448	458
14. Min. Cht - °F		410	420	428	435
15. EGT - °F		1405	1422	1436	1443
16. Torque, lb-ft		595	598	600	602
17. Obs. Bhp		227	228	228	229
18. % CO_2 (Dry)		8.53	9.08	9.57	9.87
19. % CO (Dry)		9.74	9.00	8.38	7.85
20. % O_2 (Dry)		0.21	0.21	0.21	0.21
21. HC-ppm (Wet)		2230	2074	1969	1917
22. NO_x-ppm (Wet)		168	229	283	328
23. CO_2-lb/h		232.0	243.5	254.0	258.8
24. CO-lb/h		168.6	153.6	141.6	131.0
25. O_2-lb/h		4.15	4.09	4.05	4.00
26. HC-lb/h		2.63	2.42	2.27	2.18
27. NO_x-lb/h		0.371	0.499	0.609	0.6965
28. CO-lb/Mode		0.843	0.768	0.708	0.655
29. HC-lb/Mode		0.0132	0.0121	0.0113	0.0109
30. NO_x-lb/Mode		0.00185	0.00250	0.00304	0.00348

TABLE C-15. TCM 6-285-B ENGINE NAFEC TEST DATA--CLIMB MODE
LEAN-OUT--SPARK SETTING 30° BTC

	Parameter	Mode	46	47	48	49
		Run No.	46	47	48	49
	Parameter	**Mode**	**Climb**	**Climb**	**Climb**	**Climb**
1.	Act. Baro. - inHgA		29.93	29.93	29.93	29.93
2.	Spec. Hum. - lb/lb		0.0100	0.0100	0.0100	0.0100
3.	Induct. Air Temp.-°F		128	128	128	128
4.	Cooling Air Temp.-°F		130	130	131	123
5.	Induct. Air Press.-inHgA		30.27	30.28	30.28	30.29
6.	Engine Speed - RPM		3600	3600	3600	3600
7.	Manifold Air Press.-inHgA		25.7	25.7	25.7	25.7
8.	Induct. Air Densigy-lb/ft^3		0.0682	0.0683	0.0681	0.0686
9.	Fuel Flow, W_f-lb/h		126.0	121.0	116.0	111.0
10.	Airflow, W_a-lb/h		1385.0	1412.0	1405.0	1415.0
11.	F/A (Measured) = 9 / 10		0.0910	0.0857	0.0826	0.0784
12.	Max. Cht - °F		429	436	444	450
13.	Avg. Cht - °F		425	432	440	445
14.	Min. Cht - °F		417	424	431	435
15.	EGT - °F		1336	1353	1384	1410
16.	Torque, lb-ft		542	542	553	546
17.	Obs. Bhp		186	186	190	187
18.	% CO_2 (Dry)		9.25	9.76	10.73	11.38
19.	% CO (Dry)		8.84	8.00	6.53	5.34
20.	% O_2 (Dry)		0.23	0.23	0.23	0.23
21.	HC-ppm (Wet)		2133	2003	1820	1711
22.	NO_x-ppm (Wet)		237	318	522	765
23.	CO_2-lb/h		197.1	209.4	224.8	236.6
24.	CO-lb/h		119.9	109.2	87.1	70.7
25.	O_2-lb/h		3.56	3.59	3.50	3.48
26.	HC-lb/h		1.93	1.81	1.62	1.51
27.	NO_x-lb/h		0.401	0.537	0.868	1.262
28.	CO-lb/Mode		9.988	9.101	7.256	5.888
29.	HC-lb/Mode		0.1606	0.1349	0.1349	0.1258
30.	NO_x-lb/Mode		0.0334	0.0448	0.0724	0.1052

TABLE C-16. TCM 6-285-B ENGINE NAFEC TEST DATA--CLIMB MODE LEAN-OUT--SPARK SETTING 30° BTC

		Run No.	50	51	52	53
	Parameter	Mode	Approach	Approach	Approach	Approach
1.	Act. Baro. - inHgA		29.92	29.92	29.92	29.92
2.	Spec. Hum. - lb/lb		0.0090	0.0090	0.0090	0.0090
3.	Induct. Air Temp.-°F		121	122	124	122
4.	Cooling Air Temp.-°F		123	125	127	122
5.	Induct. Air Press.-inHgA		29.92	29.92	29.92	29.92
6.	Engine Speed - RPM		3355	3400	3400	3400
7.	Manifold Air Press.-inHgA		16.5	16.5	16.5	16.5
8.	Induct. Air Density-lb/ft^3		0.0682	0.0681	0.0678	0.0681
9.	Fuel Flow, W_f-lb/h		72.0	67.0	62.0	57.0
10.	Airflow, W_a-lb/h		795.0	781.0	784.0	786.0
11.	F/A (Measured) = 9 / 10		0.0905	0.0858	0.0791	0.0725
12.	Max. Cht - °F		365	374	386	397
13.	Avg. Cht - °F		360	370	383	394
14.	Min. Cht - °F		355	367	380	389
15.	EGT - °F		1118	1150	1198	1258
16.	Torque, lb-ft		261	262	263	267
17.	Obs. Bhp		83	85	85	86
18.	% CO_2 (Dry)		8.04	9.15	10.79	12.87
19.	% CO (Dry)		10.94	9.05	6.35	3.14
20.	% O_2 (Dry)		0.31	0.30	0.30	0.32
21.	HC-ppm (Wet)		3462	2996	2544	2131
22.	NO_x-ppm (Wet)		123	208	484	1260
23.	CO_2-lb/h		102.0	110.5	126.1	145.6
24.	CO=lb/h		88.4	69.6	47.2	22.6
25.	O_2-lb/h		2.86	2.63	2.55	2.63
26.	HC-lb/h		1.79	1.50	1.25	1.01
27.	NO_x-lb/h		0.12	0.19	0.44	1.11
28.	CO-lb/Mode		8.836	6.957	4.724	2.261
29.	HC-lb/Mode		0.179	0.150	0.125	0.101
30.	NO_x-lb/Mode		0.012	0.019	0.044	0.111

TABLE C-17. TCM 6-285-B ENGINE NAFEC TEST DATA--TAXI MODE LEAN-OUT--SPARK SETTING 30° BTC

	Parameter	Mode	Run No. 82	Run No. 83	Run No. 84
			Taxi	Taxi	Taxi
1.	Act. Baro. - inHgA		30.14	30.14	30.14
2.	Spec. Hum. - lb/lb		0.0075	0.0075	0.0075
3.	Induct. Air Temp.-°F		70	70	70
4.	Cooling Air Temp.-°F		68	69	68
5.	Induct. Air Press.=inHgA		30.38	30.29	30.39
6.	Engine Speed - RPM		1790	1775	1800
7.	Manifold Air Press.-inHgA		11.0	10.8	10.9
8.	Induct. Air Density-lb/ft^3		0.0760	0.0757	0.0760
9.	Fuel Flow, W_f-lb/h		15.8	14.1	12.8
10.	Airflow, W_a-lb/h		193.5	184.5	187.7
11.	F/A (Measured) = 9 / 10		0.0817	0.0764	0.0682
12.	Max. Cht - °F		387	395	418
13.	Avg. Cht - °F		355	363	381
14.	Min. Cht - °F		281	289	294
15.	EGT - °F		710	733	748
16.	Torque, lb-ft		30	30	28
17.	Obs. Bhp		5	5	5
18.	% CO_2 (Dry)		8.71	11.19	12.28
19.	% CO (Dry)		8.81	5.30	3.82
20.	% O_2 (Dry)		0.63	0.58	0.54
21.	HC-ppm (Wet)		5133	3424	2973
22.	NO_x-ppm (Wet)		64	98	146
23.	CO_2-lb/h		25.8	30.3	33.5
24.	CO-lb/h		16.6	9.15	6.63
25.	O_2-lb/h		1.35	1.14	1.07
26.	HC-lb/h		0.612	0.391	0.334
27.	NO_x-lb/h		0.0144	0.0210	0.0306
28.	CO-lb/Mode		4.427	2.440	1.768
29.	HC-lb/Mode		0.163	0.104	0.0891
30.	NO_x-lb/Mode		0.00384	0.00560	0.00816

TABLE C-18. TCM 6-285-B ENGINE NAFEC TEST DATA--TAXI MODE LEAN-OUT--SPARK SETTING 30° BTC

	Parameter	Run No.	126	127	128
		Mode	Taxi	Taxi	Taxi
1.	Act. Baro. - inHgA		28.80	28.80	28.50
2.	Spec. Hum. - lb/lb		0.0110	0.0110	0.0110
3.	Induct. Air Temp.-°F		104	103	102
4.	Cooling Air Temp.-°F		109	113	109
5.	Induct. Air Press.-inHgA		29.19	29.19	28.87
6.	Engine Soeed - RPM		1800	1820	1800
7.	Manifold Air Press.-inHgA		11.4	11.3	11.4
8.	Induct. Air Density=lb/ft^3		0.0686	0.0687	0.0681
9.	Fuel Flow, W_f-lb/h		17.5	16.0	14.5
10.	Airflow, W_a-lb/h		201.6	200.9	207.6
11.	F/A (Measured) = 9 / 10		0.0868	0.0796	0.0698
12.	Max. Cht - °F		307	293	304
13.	Avg. Cht - °F		301	288	298
14.	Min. Cht - °F		293	283	293
15.	EGT - °F		721	736	786
16.	Torque, lb-ft		-	-	-
17.	Obs. Bhp		-	-	-
18.	% CO_2 (Dry)		9.18	10.88	12.55
19.	% CO (Dry)		8.20	5.57	3.16
20.	% O_2 (Dry)		0.54	0.52	0.47
21.	HC-ppm (Wet)		5347	3947	2748
22.	NO_x-ppm (Wet)		62	94	134
23.	CO_2-lb/h		27.9	32.0	37.4
24.	CO-lb/h		15.9	10.4	5.99
25.	O_2-lb/h		1.19	1.11	1.02
26.	HC-lb/h		0.694	0.498	0.344
27.	NO_x-lb/h		0.0150	0.0222	0.0315
28.	CO-lb/Mode		4.240	2.773	1.597
29.	HC-lb/Mode		0.185	0.133	0.0917
30.	NO_x-lb/Mode		0.00400	0.00592	0.00840

AD-A074 338 NATIONAL AVIATION FACILITIES EXPERIMENTAL CENTER ATL--ETC F/G 21/7
EXHAUST EMISSIONS CHARACTERISTICS FOR A GENERAL AVIATION LIGHT---ETC(U)
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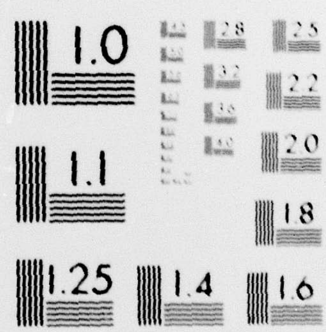

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TABLE C-19. TOTAL EMISSIONS CHARACTERISTICS--TCM 6-285 B ENGINE--SEA LEVEL STANDARD DAY

Mode	CO (lb/h)	CO (lb/Mode)	HC (lb/h)	HC (lb/Mode)	NO_x (lb/h)	NO_x (lb/Mod)	(F/A)	Max. (CHT-°F)
Taxi (16.9 - Min.)	21.0	5.600	0.880	0.235	0.0100	0.0027	0.0900	365
Takeoff (0.3 - Min.)	117.5	0.588	1.400	0.007	0.8000	0.0040	0.0880	440
Climb (5.0 - Min.)	86.5	7.208	1.220	0.102	0.7250	0.0604	0.0820	425
Approach (6.0 - Min.)	50.0	5.000	1.000	0.100	0.3000	0.0300	0.0785	365
lb/Cycle		18.396		0.444		0.0971		
lb/Cycle/RBHP		0.065		0.0016		0.00034		
Federal Limit		0.042		0.0019		0.0015		
Diff. = 6 - 7		0.023		- .0003		- .00116		
(8 ÷ 7) x 100		53.7		-18.0		-77.3		
% of STD. = 9 + 100		153.7		82.0		22.7		

	W_f (lb/h)	W_a (lb/h)
Takeoff (100%)	160	1818
Climb (80%)	122	1488
Approach (40%)	67	854
Taxi	18	200

TABLE C-20. TOTAL EMISSIONS CHARACTERISTICS--TCM 6-285 B ENGINE--SEA LEVEL WARM DAY (80° F)

Mode	CO (lb/h)	CO (lb/Mode)	HC (lb/h)	HC (lb/Mode)	NO_x (lb/h)	NO_x (lb/Mod)	(F/A)	Max. (CHT-°F)
Taxi (16.0 - Min.)	19.7	5.253	0.930	0.248	0.0100	0.0027	0.0900	385
Takeoff (0.3 - Min.)	122.0	0.610	1.680	0.008	0.7500	0.0038	0.0905	455
Climb (5.0 - Min.)	95.0	7.917	1.400	0.117	0.5800	0.0483	0.0845	430
Approach (6.0 - Min.)	58.0	5.800	1.190	0.119	0.3000	0.0300	0.0830	375
lb/Cycle		19.580		0.492		0.0848		
lb/Cycle/RBHP		0.069		0.0017		0.0003		
Federal Limit		0.042		0.0019		0.0015		
Diff. = 6 - 7		.027		- .0002		- .0012		
(8 ÷ 7) x 100		64.3		-9.1		-80.2		
% of STD. = 9 + 100		164.3		90.9		19.8		

	W_f (lb/h)	W_a (lb/h)
Takeoff (100%)	160	1768
Climb (80%)	122	1444
Approach (40%)	67	807
Taxi	18	200

TABLE C-21. TOTAL EMISSIONS CHARACTERISTICS--TCM 6-285 B ENGINE--SEA LEVEL HOT DAY (100°F)

Mode	CO (lb/h)	CO (lb/Mode)	HC (lb/h)	HC (lb/Mode)	NO_x (lb/h)	NO_x (lb/Mod)	(F/A)	Max. (CHT-°F)
Taxi (16.0 - Min.)	18.4	4.907	0.900	0.240	0.0100	0.0027	0.0900	305
Takeoff (0.3 - Min.)	127.0	0.635	1.950	0.010	0.7000	0.0035	0.0920	467
Climb (5.0 - Min.)	103.0	8.583	1.580	0.132	0.5250	0.0438	0.0870	435
Approach (6.0 - Min.)	65.0	6.500	1.360	0.136	0.2500	0.0250	0.0835	375
lb/Cycle		20.625		0.518		0.0750		
lb/Cycle/RBHP		0.0724		0.00182		0.00026		
Federal Limit		0.042		0.0019		0.0015		
Diff. = 6 - 7		0.0304		- .00008		- .00124		
(8 ÷ 7) x 100		72.3		-4.2		-82.5		
% of STD. = 9 + 100		172.3		95.8		17.5		

	W_f (lb/h)	W_a (lb/h)
Takeoff (100%)	160	1739
Climb (80%)	122	1402
Approach (40%)	67	802
Taxi	18	200